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The Ontogeny of Basicranial Flexion in Children of African and European Ancestry

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Abstract
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Keywords
ontogeny, basicranium, cranial base, flexion, angle, sex, race, Homo, children, growth

Disciplines
Anthropology

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THE ONTOGENY OF BASICRANIAL FLEXION IN CHILDREN OF AFRICAN AND EUROPEAN ANCESTRY

By

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In

Anthropology

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Department of Anthropology

University of Pennsylvania

Thesis Advisor: Dr. Janet Monge

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Table of Contents

Abstract

This study examined ontogenetic changes in the cranial base angle in individuals between the ages of 2 and 25 years old. Also, variation in the cranial base angle between males and females, and between blacks and whites was examined. This study was initially conceived as an examination of the spectrum of human variation in the growth and development of the basicranium, as well as its possible correlation to language development. This study was designed to replicate Lieberman and McCarthy's 1999 examination of the processes of basicranial flexion, with additional consideration of variation by sex and by race. To that end, this study assessed a sample of 39 individuals, composed of 10 black males, 10 black females, 10 white males, and 9 white females. Individuals were drawn from the Krogman Growth Study, a mixed longitudinal and cross-sectional dataset housed at the Penn Museum. A total of 7 cranial base angles were measured, of which 5 were borrowed from Lieberman and McCarthy (designated CBA 1-5), and 2 from Zuckerman (1955) (designated Z1-2), to more thoroughly capture changes in spatial relationships between cranial bones. Results largely indicated that no significant increase or decrease in cranial base angle occurs after the cessation of brain growth at age 2. However, the mean values of 5 out of the 7 cranial base angles were shown to be statistically significantly different by sex, and 3 out of 7 angles revealed statistically significant difference by race. An examination of the Z1-2 angles against CBA 1-5 using regression indicated that, although Zuckerman's angles did not capture any new variation by sex compared to CBA 1-5, they did reveal an additional spatial relationship which varied by race. Therefore, results confirm Lieberman and McCarthy's assessment that cranial base flexion does not change significantly past the age of two. In addition, results of this study indicate that cranial base angle is also dimorphic by race, a factor which Lieberman and McCarthy did not assess. No conclusions could be drawn as to the relationship of CBA 5 to language development.

Chapter 1: Background and Introduction

Background: Toward the Modern Techniques of Cranial Analysis

For much of recorded history, human beings have sought to answer the fundamental question: "who are we?" What is it that makes us human, and how do we distinguish ourselves from the world around us? As is immortalized in Diogenes Laërtius' third-century work, *Lives and Opinions of the Eminent Philosophers*, "Plato defined man thus: 'Man is a two-footed, featherless animal,' and was much praised for the definition; so Diogenes plucked a cock and brought it into his school, and said, 'This is Plato's man.' On which account this addition was made to the definition, 'With broad flat nails' (Laërtius: 232)." The spirit of scientific curiosity was not satisfied with this definition, however, and intellectuals continued to search for a method of classifying man's place in nature.

One of the most enduring systems of classification was introduced in the 18th century by Swedish naturalist Carolus Linnaeus (1707-1788). The system of Linnaean taxonomy classified all life along a hierarchy according to biological characteristics, firmly separating man from chicken once and for all. However, by placing man at the top of the hierarchy, Linnaeus effectively set humans apart from the natural world, on a pedestal of superiority, an ideal which would become central to Western scientific inquiry. Linnaeus also sowed the seeds of what would later evolve into scientific racism, classifying the genus Homo into four subdivisions – Europeaeus, Americanus, Asiaticus, and Africanus – based on the physical and behavioral characteristics of each race (Smedley, 2011: 218). These early assumptions by Linnaeus reflect the tendency of 18th-century European science to conflate biological race with (assumed) innate behavioral characteristics (Smedley, 2011: 219).

The central question had now become "how do we distinguish ourselves from each other?" By the latter part of the 18th century, German professor Johann Blumenbach (1752-1840) had proposed the classification of humankind into five "varieties" or "races" corresponding to the major regions of the world (Blumenbach, 1781; Smedley, 2011: 220). These five "races" – Caucasian, Mongolian, Ethiopian, American, and Malay – are still widely used today (Blumenbach, 1781; Smedley, 2011: 220). The popularization of Blumenbach's theories of race coupled with the rise of comparative anatomy and new anthropometric measuring techniques in the late 18th century encouraged a confluence of these early conceptions of race science with the much older field of cranial study.

Since the days of Herodotus (c.480-c.429 BCE), the human skull has been the focus of study by physicians and intellectuals (Meijer, 1999: 101).[i] However, it was not until the late 15th and early 16th century that Renaissance artists and anatomists (such as, Andreas Vesalius, Bartolomeo Eustachi, and Albrecht Dürer) began to systematically and empirically study the form and components of the skull that variations in skull shape were truly noted (Meijer, 1999: 101-2; Kemp, 2010). This practice of precise, systematic measurement of the skull that had begun to emerge by the early 16th century was the beginning of what is now known as craniology. Craniology, or the study of the skull, employed measurements of the size of the braincase, the angle of the face, or other cranial features to quantify human variation (Sowerwine, 2003: 294).

In the 18th century, the evolution of craniometric techniques was driven in large part by the development of scientific racism. The earliest application of these techniques to questions of race can be traced to anatomist Pieter Camper's (1722-1789) 1770 study of the "facial angle" between various human races and apes (Meijer, 1999: 108). This angle, connecting the line between the front of the incisor teeth and the most prominent part of the forehead (the frontal

bone) with a line drawn from the earhole (external auditory canal) to the base of the nose, measured the slope of the forehead and the degree of projection of the jaw (Meijer, 1999: 102-108). This measurement provided a means of reducing a variety of head shapes to a single quantifiable factor (Meijer, 1999: 102, 108). Influenced in particular by Dürer's studies of human proportion, Camper identified the facial angle as an objective marker of "ideal beauty" (Meijer, 1999: 107, 160). A larger facial angle, corresponding to a higher forehead and a less-projecting jaw, as seen in Europeans, was considered superior, as it approached the (unattainable) Greco-Roman archetype of beauty, while a lower angle, as seen in Africans, was dismissed by Camper as inferior and more closely resembling apes (Meijer, 1999: 107; Brace, 2005: 33). In the same vein, Blumenbach's five "varieties" of man, which he proposed in 1775, were categorized into "races" according to features of cranial morphology (Blumenbach, 1781: 99, 303-319). Following the publication of Camper and Blumenbach's conceptualization of the "races" through cranial measurement, craniology was cemented as a distinct field of study and would go on to focus primarily on the differentiation of the human "races" from each other and, in comparison to the primates (Meijer, 1999: 171-2).

By the 19th century, the evident variations in skull shape and size led to the increasingly popular assumption among naturalists that skull size (brain size in particular) was correlated with intelligence (Haller, 1971: 18). This association had its roots primarily in the principles of phrenology, a pseudo-science founded in the late 18th century by German physiologist Franz Joseph Gall (1758-1828) (Gall, 1810; Haller, 1971: 14; Serletis and Pait, 2016: 1868). Originally termed "cranioscopy," phrenology claimed to be able to infer localization of specific brain functions through the examination of external anatomical landmarks of the cranium (Serletis and Pait, 2016: 1867-8). Although phrenology was discredited and disavowed by the scientific community by the mid-19th century, (Serletis and Pait, 2016: 1868) the link between cranial

morphology and brain function had been made, and, as with Linnaeus's classifications of race, physical traits and behavioral attributes were again conflated.

Firmly grounded in the 18th-century scientific paradigm, Philadelphia physician Samuel George Morton (1799-1851) subscribed to the principles of phrenology and accepted the assumption that brain size corresponded directly to intellectual capacity (Morton, 1839: i). Widely known as the father of scientific racism, Morton is most famous for his claims that the shape of the cranium and the volume of the braincase could objectively define racial categories (Renschler and Monge, 2008: 34). Ultimately, Morton aimed to understand human racial variations through objectivity and the scientific method (Renschler and Monge, 2008: 34). To this end, Morton amassed a collection of 867 skulls, the largest in the world, and systematically measured the internal volume of each skull in an effort to determine the average brain size of each racial category (Morton, 1849: iii-iv; Gould, 1996: 85). Morton defined five races similar to Blumenbach's arrangement – Caucasian, Mongolian, Malay, American, and Ethiopian – according to physical and behavioral characteristics (Morton, 1839: 5-6; Morton, 1849: ix). Morton also identified several subfamilies, or "primary races" within each larger racial category (Morton, 1849: ix).

Morton thoroughly analyzed the cranial dimensions of each skull, measuring a total of thirteen cranial features, including longitudinal diameter, parietal diameter, frontal diameter, vertical diameter, inter-mastoid arch, inter-mastoid line, occipito-frontal arch, horizontal periphery, internal capacity, capacity of the anterior chamber, capacity of the posterior chamber, capacity of the coronal region, and facial angle (Morton, 1839). The internal capacity, in particular, was measured by filling the cranial cavity with lead shot (or BBs) measuring 1/8 inch in diameter and recording the volume using a graduated cylinder (Gould, 1996: 85). On the whole, as illustrated in his *Catalogue of Skulls of Man and the Inferior Animals* (1849), Morton's

measurements revealed distinctly different mean brain sizes between the racial categories that he had identified – with the Caucasian group average ranking first, and the Negro group last (Morton, 1849; Gould, 1996: 86). According to the principles of phrenology, Morton's craniometric data supported the pre-existing Western conceptions of racial hierarchy and 'proved' that brain size, and, therefore, intelligence and intellectual capacity, were stratified by race (Morton, 1839: 276-277; Gould, 1996: 100).

Recently, Morton's analysis has faced accusations of unconscious bias, most famously by Stephen Jay Gould in his 1981 work *The Mismeasure of Man*. Gould claimed that Morton's racial groupings were inaccurate and biased, that his measurements were inconsistent, and that the influence of body size (allometry) on each racial average was overlooked (Gould, 1996: 100). However, in the years since Gould's publication, a team of scientists at the Penn Museum of Archaeology and Anthropology, where Morton's cranial collection is housed, re-measured Morton's crania using his technique and compared the results against his reported data (Renschler and Monge, 2008: 30; Lewis *et al.*, 2011: 5). This study determined that, despite failing to acknowledge that sex or stature may have influenced his reported Means, Morton's measurements were, on the whole, very accurate (Lewis *et al.*, 2011: 5).

Following from the assumption that brain size correlated with intelligence, craniology and cranial measurements became established as the basis for physical anthropology (Sowerwine, 2003: 294). Paul Broca (1824-1880), a renowned French surgeon, neurologist, and anthropologist, and a leading expert in craniology, instilled this paradigm in his School of Anthropology of Paris, where it soon emerged as the central axiom of 19th century thought (Sowerwine, 2003: 290-294; Sagan, 1979: 8).

However, in 1912, a significant blow was delivered to the racialized foundations of craniology by American anthropological giant Franz Boas (1858-1942). Boas was perhaps the

single most active combatant of racism and race science among all American scientists (Barkan, 1992: 281). Boas's 1912 study, "Changes in the Bodily Form of Descendants of Immigrants," revealed that, between immigrant parents and their American-born children, inheritance/heredity of the cephalic index (a ratio of the maximum breadth of the skull to its maximum length) was very low (Boas, 1912: 546, 550). In Boas's own words, "… the two races in Europe are quite distinct, but their descendants born in America are very much alike" (Boas, 1912: 550). The cranial dimensions of these American-born children, Boas discovered, correlated directly with stature and weight, which were themselves dependent on the size of the family (Boas, 1912: 530). Thus, Boas concluded that, regardless of race, the environment rather than heredity was the driving factor behind changes in cranial morphology across generations (Boas, 1912: 530). This, and many other studies and anti-racist efforts by Boas, endeavored to show that "individual heredity and racial heredity are entirely different things and that while we may find that certain characteristic traits are inherited in a family, the race is altogether too complex to infer that racial characteristics as such are inherited" (Barkan, 1992: 283). As a result of this and subsequent studies, racism (and the dominance of craniology) slowly began to retreat from professional science (Barkan, 1992: 285).

After the outbreak of World War II, American opinions shifted even further away from Nazi ideology, openly condemning not only Nazi race science, but also racism in general. As a result of this complete reversal in attitudes towards racial separation and biologically determinable intelligence, the practice of craniology was finally cast aside. In its place arose the system of "New Physical Anthropology" (Fuentes, 2010: 2). Proposed by Sherwood Washburn in 1951, the "New Physical Anthropology" represented a move away from measurement and classification and towards a multidisciplinary and interdisciplinary focus on the processes and mechanisms of evolutionary change (Fuentes, 2010: 2). In light of innovations in evolutionary

thinking during the 1930s-1950s, namely the rise of the modern synthesis, which emphasized the importance of the environment on phenotypic variation, Washburn determined that the practices of measurement and forming of taxonomies without consideration to behavior, form, and development were inhibiting true understanding of evolution, form, and function (Washburn, 1951; Fuentes, 2010: 3). The model of physical anthropology proposed by Washburn was, therefore, inclusive of human behavior, biology, and history, and is, as a result, both biological and anthropological (Washburn, 1951; Fuentes, 2010: 2).[ii]

Under the new model, hierarchical classifications of race and the link between brain size and intelligence espoused by Morton and Broca were left by the wayside as a result of the shift away from outdated methodologies and perspectives (Fuentes, 2010: 4). However, despite innovations in methods, the forms of measurement and classification that arose in the 19th century were not abandoned, and many are still used today in studies of paleoanthropology, forensic anthropology, human variation, and medicine (Fuentes, 2010: 5). Nonetheless, these measurements are no longer limited to physical crania and are now often performed on digitally produced scans, which by their nature require new measurement methods and techniques of analysis. Some of the most well-known of these imaging techniques include radiographs (or X-Rays), computed tomography (CT) scans, and magnetic resonance imaging (MRI) scans.

These modern methods of scanning allow for greater visibility of the various bones and internal structures of the cranium (Renschler and Monge, 2008: 35; Finlay, 1980: 321). In addition, they are also highly suited to mathematical analysis (CT scans and MRIs, in particular), and, using newly developed software, cranial features and geometry can be measured, and internal cranial volume calculated quickly and to a high degree of accuracy (Renschler and Monge, 2008: 35; Nave *et al.*, 2018: 1). Radiographs are among the older of the "modern" methods and have been used to image skulls since the 1930s,[iii] yet they remain one of the most

widely used tools of cephalometric analysis today. The introduction of radiograph images to cranial analysis opened up new avenues of analysis and led to the development of new craniometric and cephalometric measurements (Finlay, 1980: 321). Apart from its importance to biological anthropology (and centrality to the present study), radiographic cephalometry remains the most widely used method for the treatment and correction of dental structures (Finlay, 1980: 312).

The cranial base angle in particular (which will be the focus of this study) is most commonly measured from lateral cephalometric radiographs (Simpson, 2014). Although other methods exist, such as the surgical implantation and tracking the locations of metallic markers at various points in the cranium (Bjork and Skieller, 1972), non-invasive methods are preferable in studies of human samples. However, despite their widespread use, some drawbacks of the use of radiographs have been noted (Bookstein, 1983; Moyers and Bookstein, 1979; Quintero *et al.*, 1999). Because a radiograph is a two-dimensional representation of a three-dimensional structure, tracings made, and angles measured from radiographs do not necessarily capture the "anatomic truth" (Quintero *et al.*, 1999: 491; Bookstein, 1983; Moyers and Bookstein, 1979; Simpson, 2014). The flattening effect of rendering a three-dimensional structure in two-dimensions also results in some degree of parallax, which may affect the perceived alignment and positioning of cranial structures relative to their distance from the imaging plane (Quintero *et al.*, 1999: 492; Bookstein, 1983; Moyers and Bookstein, 1979; Simpson, 2014). In addition, the popular technique of measuring lines and angles between points on radiographs neglects to consider that growth is not always linear along the midline, which may result in mischaracterizations of growth trends (Bookstein, 1983; Moyers and Bookstein, 1979; Simpson, 2014).

Further drawbacks include distorted or blurry images, poorly defined outlines of cranial bones, and inconsistent patient positioning, all of which cause heightened uncertainty in cranial landmark location and measurement error (Quintero *et al.*, 1999; Wei, 1968). In fact, this form of uncertainty is very common among studies conducted on radiographs, and many authors emphasize the importance of establishing the reliability of landmark location before drawing conclusions (Quintero *et al.*, 1999; Bookstein, 1983; Moyers and Bookstein, 1979; Simpson, 2014). However, despite these limitations, radiographs have several significant advantages: exposure and measurement protocols are easily standardized across studies, the process is non-invasive, a longitudinal series can easily be produced for one individual over many years, and a large, comprehensive pool of radiographs and accompanying demographic information is already well established (Simpson, 2014). As a result, radiographs remain one of the most commonly used tools in cephalometric analysis (Quintero *et al.*, 1999).

So, what can the human skull actually reveal about the nature of humans? This question has driven human cranial studies for centuries, spanning several centuries and several schools of thought. Perspectives on racism and race science were central to the development of cranial measurement and analytical techniques. Modern cephalometric analysis, in its questions and assessments, should be conducted in light of the history of the discipline, so as not to repeat the mistakes of the past. Thus, it is into this context that the present study is introduced. Cognizant of the biases and mischaracterizations that shaped the field, the author will review and reexamine previous standards of craniofacial growth in the context of age, sex, and race, primarily through an examination of lateral cranial radiographs to determine ontogenetic trends in the cranial base angle.

Introduction to the Cranial Base Angle

What We Know About the Cranial Base: A Brief Review of the Literature

The cranial base, also called the basicranium, has been identified as the oldest component of the modern human craniofacial skeleton – the result of anterior cephalization occurring early in animal evolution (Kardong, 1995; Larsen, 1998; Simpson, 2014). Composed of the ethmoid, sphenoid, and basioccipital bones, the cranial base is closely related to many cranial structures and processes. The cranial base acts as a support for the braincase and a suspensory structure for the soft tissue structures responsible for respiration, swallowing, and vocalization (Simpson, 2014). It is also closely associated with the development of the neurocranium and facial skeleton, including the inner ear, nasal fossa, and eye orbits (Simpson, 2014). As a result, the cranial base is central to cranial anatomy and development and has been widely studied in the contexts of primatology, comparative anatomy, and human evolution (Lieberman & McCarthy, 1999: 487; Simpson, 2014).

Over the course of human development, both prenatal and postnatal, the endocranial bones comprising the cranial base undergo flexion or extension relative to each other (Lieberman & McCarthy, 1999: 487). Flexion and extension occur when the inferior aspect of the angle between three points on the cranial base (or between two basicranial planes) decreases or increases, respectively (Lieberman & McCarthy, 1999: 487). These spatial relationships can be quantified through the measurement of the cranial base angle. The cranial base angle (or CBA) is a collective measure of the angles between various cranial points in the prechordal and postchordal planes (Lieberman and McCarthy, 1999: 489). Flexion and extension of CBA occur at the spheno-ethmoid synchondrosis (SES), the mid-sphenoidal synchondrosis (MSS), and/or the spheno-occipital synchondrosis (SOS) (Lieberman and McCarthy, 1999: 488). These occur either through a rotation of each bone on either side of the synchondrosis due to deposition and

resorption of bone or through interstitial growth at the synchondrosis, which results in a hinge-like movement that reduces CBA (Lieberman and McCarthy, 1999: 489). There is much variation in the timing and type of synchondrosis alteration between humans and primates, and studies of these processes have drawn conflicting conclusions about the timing of fusion of these features (Lieberman and McCarthy, 1999: 489; Zuckerman, 1955).

Although the primate order is unique among mammals due to a highly flexed CBA, humans, especially, possess an acutely flexed CBA, which has been widely researched in conjunction with many associated aspects of craniofacial anatomy and development (Ross and Henneberg, 1995; Lieberman *et al.*, 2001: 126). In order to contextualize the present study within the current state of research, extant literature surrounding the cranial base and its relation to craniofacial morphology will be reviewed. To that end, popular hypotheses correlating basicranial flexion with bipedal posture, neural development, facial kyphosis, and vocal tract and upper respiratory structures will be discussed.

Within the published literature, studies of the cranial base tend to examine the feature in relation to a) bipedalism and posture (Weidenreich, 1924, 1941, 1945; Dabelow, 1929; Dmoch, 1975, 1976; Ashton, 1957; Bolk, 1915; Strait, 2001; Strait and Ross, 1999; Solow and Tallgren, 1976; Moss, 1961; Riesenfeld, 1967, 1969), b) neural growth (Gould, 1977; Ross, 1993; Ross and Henneberg, 1995; Ross and Ravosa, 1993; Strait, 1998; Strait and Ross, 1999; Moss, 1958; Biegert, 1963; Enlow, 1968; Gould, 1977; Dean, 1988; Spoor, 1997), c) facial kyphosis (Ashton, 1957; Biegert, 1963; Sirianni & Swindler, 1979; Enlow, 1990), and d) speech and language capacity (Laitman, 1976; Laitman *et al.*, 1978; Laitman and Heimbuch, 1982; Laitman, 1985; Lieberman and Crelin, 1971, Lieberman *et al.*, 1972). While these four approaches are not mutually exclusive, each occasionally necessitates the use of differing measures of the cranial base angle to quantify differing spatial relationships between various cranial bones.

Angle	Planes utilized (P=posterior; A=anterior)	References
External cranial base angle, nasion–sella–basion	P: basion–sella A: sella–nasion	Björk, 1951, 1955; Stamrud, 1959; Melsen, 1969; George, 1978; etc.
Landzert's sphenoidal angle, clivus/clival angle*, CBA, planum angle	P: clival plane A: ethmoidal plane (planum sphenoideum (-ale))	Landzert, 1866; Howell, 1951; Biegert, 1957; Moss, 1958; Hofer, 1957, 1960; Hofer & Spatz, 1963; Angst, 1967; Cartmill, 1970; Schäfer, 1975; Dmoch, 1975*a*,*b*, 1976; Ross & Ravosa, 1993; Ross & Henneberg, 1995
Clivus angle*	P: clival plane A: palate horizontal	Flügel *et al.*, 1993
Clival angle*	P: clival plane A: sphenoidale–fronton	George, 1978
Ethmoidal angle, internal cranial base angle	P: basion–sella A: sella–ethmoidale	Björk, 1958; Stamrud, 1959
Spheno–ethmoidal angle, cranio–facial axis	P: basion–prosphenion A: prosphenion–nasion	Huxley, 1867; Topinard, 1890; Duckworth, 1904; Cameron, 1924, 1925; Zuckerman, 1926, 1955; Ford, 1956; Ashton, 1957
Cameron's cranio–facial axis	P: basion–pituitary point A: pituitary point–nasion	Cameron, 1924, 1925, 1927*a*,*b*, 1930
Basioccipito–septal angle	P: basion–pituitary point A: pituitary point–septal point	Ford, 1956
Bolton's external cranial base angle	P: Bolton point–sella A: sella–nasion	Broadbent, 1937; Brodie, 1941, 1953; Anderson & Popovich, 1983
Anterior cranial base angle	P: clival plane A: prosphenion–anterior cribriform point (ACP)	Scott, 1958; Cramer, 1977
Internal cranial base angle, fronton–sphenoidale–basion	P: basion–sphenoidale A: sphenoidale–fronton	George, 1978
Internal cranial base angle, fronton–sella–basion	P: basion–sella A: sella–fronton	George, 1978
Internal cranial base angle, foramen caecum–sella–basion	P: basion–sella A: sella–foramen caecum	Cousin *et al.*, 1981†; Spoor, 1997
External cranial base angle, nasion–sphenoidale–basion	P: basion–sphenoidale A: sphenoidale–nasion	George, 1978
Orbital angle	P: clival plane A: plane of superior orbital roof	Moss, 1958
Planum angle (PANG)	P: basion–sella A: planum sphenoidale	Antón, 1989
Orbital angle (OANG)	P: basion–sella A: plane of superior orbital roof	Antón, 1989

*The term "clivus angle" or "clival angle" has been used to denote a variety of different cranial base angles.
†Cousin *et al.*, 1981 differ slightly because they used the anterior-most point on the cribriform plate instead of the foramen caecum.

Table 1: Summary of the most commonly used cranial base angles (after Lieberman and McCarthy, 1999).

The basicranium has a complex topography, and, as such, flexion is capable of being calculated from various points, either endocranially or exocranially (Laitman *et al.*, 1978, 469).

Table 1 above (after Lieberman *et al.*, 1999: 490) summarizes the most commonly used cranial base angles. As Lieberman explains, the basion-sella-nasion (Ba-S-Na) angle is the most commonly used throughout cranial base studies; however, it introduces variation relative to nasal and overall facial growth, which is not a part of the cranial base (Lieberman and McCarthy, 1999). Other angles used to attempt to correct for this problem may capture other sources of variation, due to the differential growth rates and patterns of the many cranial bones, each of which changes independently (Lieberman and McCarthy, 1999). Many studies have employed slightly different measures of cranial base flexion in order to capture the spatial relationships of interest. For example, studies of the correlation between the basicranium and vocal tract structures by Laitman made use of exocranial measurements (as well as endocranial) of CBA in order to test the relationship of the cranial base to directly underlying soft tissue structures (Laitman, 1976, 1978, 1979, 1982).

Perhaps the earliest approach to studying the basicranium was in its structural relation to bipedalism. Studies of the basicranial line conducted by Bolk in 1915 and Ashton in 1957 examined the position and tilt of the foramen magnum in various species of monkeys and apes. These studies revealed that the foramen magnum is positioned near the occipital in basal, arboreal primates, while anthropoid apes show a more ventrally shifted foramen magnum compared to its positioning in the center of the skull in modern humans and hominin fossils (Bolk, 1915; Ashton, 1957; Simpson, 2014). Based on these trends, Strait (2001) suggested that, as a result of changing skeletal architecture, the shifting center of mass that accompanied the evolution of bipedalism required a re-positioning of the foramen magnum, and, therefore a more flexed cranial base (Bolk, 1915; Ashton, 1957; Strait, 2001; Simpson, 2014).

However, posture is not the only factor associated with increased basicranial flexion. Ashton (1957) also acknowledged that postnatal growth changes in the basicranial axis revealed

that differences in growth between monkeys, apes, and humans were primarily the result of variations in relative cranial size and facial morphology rather than posture (Ashton, 1957). In addition, recent studies of basicranial flexion relative to the positioning of the head over the neck in modern humans by Strait and Ross in 1999 and Strait in 2001 concluded that brain size was equally if not more influential than posture on the morphology of the basicranium (Strait and Ross, 1999; Strait, 2001). Strait (2001) also concluded that while CBA was correlated with the positioning of the head relative to the neck in cercopithecoids, in humans CBA was more closely associated with brain size (although the correlation was not strong) (Strait, 2001).

The correlation between increased basicranial flexion and increased brain size gained further support from Gould (1977), Ross and Ravosa (1993), Ross and Henneberg (1995), Spoor (1997), and Strait (1999). Ross and Ravosa (1993) investigated haplorrhine and strepsirrhine primates, while Spoor (1997) examined modern humans and other hominins (Ross and Ravosa, 1993; Spoor, 1997). Both concluded that increased flexure of the cranial base was related to a shortened basicranium, an inferiorly facing foramen magnum, and an increase in brain size, likely indicating that postural adaptations and increased brain size are not mutually exclusive in their effects on the basicranium (Ross and Ravosa, 1993; Spoor, 1997). However, interestingly, Ross and Ravosa discovered that this trend was present in haplorrhines, yet not in strepsirrhines (Ross and Ravosa, 1993). However, trends of flexion in CBA do not correlate exactly with increasing brain size. Although Strait (1999) observed a significant correlation between brain size and CBA in various primate species, Ross and Henneberg (1995) determined through an examination of basicranial flexion and brain volume in fossil hominins that cranial base flexion has remained largely unchanged since *Australopithecus africanus*, and has therefore reached maximum angulation, regardless of continuing increases in brain volume (Ross and Henneberg, 1995).

However, according to Strait (1999), although there is evidence for the presence of a correlation between brain size and increasing basicranial flexion across various primate taxa, the relationship is not directly causal, indicating the presence of additional factors (Strait, 1999). Further research has indicated that the cranial base is also closely influenced by the morphology of the facial skeleton. In his study of postnatal growth changes in primates, Ashton (1957) concluded that differences in ontogeny of the CBA are related to variations in both cranial and facial dimensions (Ashton, 1957). In addition, Ashton determined that the foramino-basal angle, in particular, became more acute in response to the eruption of the permanent teeth, further indicating that CBA is influenced by facial morphology (Ashton, 1957). Many other researchers, including Biegert (1963), Sirianni & Swindler (1979), and Kasai *et al.* (1995), have lent additional support to this hypothesis.

Furthermore, variation in facial morphology, and therefore in cranial base flexion, resulting from both sexual and racial variation has been examined. Neaux *et al.* (2015) found evidence for sexual dimorphism in basicranial flexion, while Kasai *et al.* (1993), Kavitha and Karthik (2012), and Cossio *et al.* (2016) noted that the shape and flexion of the basicranium are also influenced by race. Neaux *et al.* examined cranial base flexion in *Pan*, *Gorilla*, and *Homo* and determined that sexual dimorphism was present not only in the more obviously dimorphic chimpanzees and gorillas but also to a significant degree in humans as well. Facial prognathism was also found to be significantly distinct between the sexes for all three taxa. In addition, Enlow (1971) determined that the morphology of the cranial base is related to maxillary growth and is therefore influenced by facial prognathism.

Interestingly, however, although significant evidence for sexual dimorphism in cranial base flexion has been found in these studies, others have failed to find any significant sexual dimorphism (Mathias de Almieda *et al.*, 2017). These conflicting results may suggest that sexual

dimorphism in the cranial base may be more pronounced in some populations than in others, or that sexual dimorphism in facial morphology is only one of many factors affecting the cranial base. Therefore, in light of these conflicting results, the present study will contribute to this debate by conducting an analysis of variation in basicranial morphology by sex.

Research has also indicated evidence for racial variation in cranial base morphology. Kavitha and Karthik (2012) determined that, between Africans, Mongoloids, and Caucasians, craniofacial variation was statistically significantly distinct, not only in overall head shape but also in facial morphology and prognathism. In addition, Mathias de Almieda *et al.* (2017) found the length of the cranial base to be greater in Japanese than in Caucasian females. Chin *et al.* (2014) and Kasai (1995), in an assessment of angular and linear cranial base morphology, hypothesized that the cranial base angle was directly related to the sagittal position of the jaws, or the degree of prognathism of the maxilla and mandible, which has been observed to vary between races (Chin *et al.* 2014, Kasai 1995). Kasai (1995) also found evidence to suggest that both cranial base shape and size are related to facial morphology, specifically facial length, inclination of the maxilla, and maxillary and mandibular prognathism (Kasai 1995). Although it does not appear as though racial dimorphism in the cranial base is disputed, many studies that have examined the influence of race on cranial base morphology tend to focus on the effect of the cranial base on the prevalence of dental malocclusions. This results in what is perhaps a unilateral approach to the measurement and analysis of racial variation in the cranial base. Therefore, this study will also attempt to analyze racial variation in the cranial base using a variety of angle measures that may not be as directly influenced by maxillary prognathism.

It also has been suggested that changes in the positioning of the face not only resulted in changes to the basicranium, but also led to a reduction in the horizontal dimensions of the vocal tract, resulting in the rearrangement of the position of the vocal tract, tongue, and hyoid bone

(Enlow, 1990). Such an association implies a potential connection between the basicranium and the spatial arrangement of the oral cavity and upper airway. In line with these findings, several studies spearheaded by Laitman in the late 1970s suggested a possible structural association between the basicranium and the capacity for speech production. The cranial base forms the roof of the pharynx, which is responsible for resonance and the production of intonation. The larynx, responsible for the production of phonation through the modulation of airflow from the lungs, lies below. Laitman (1976) introduced the theory that basicranial flexion exerts a structural influence on the position and orientation of the larynx and pharynx (Laitman, 1982: 324; Laitman and Crelin, 1976; Laitman *et al.*, 1978; Lieberman *et al.*, 1992). In 1978, 1982, and 1985, Laitman fleshed out this theory further, exploring the relationship between changes in basicranial flexion and the upper respiratory systems of humans and several species of primates (Laitman *et al.*, 1978: 467).

Unlike many of the previous studies discussed, Laitman *et al.* measured exocranial flexion from five points on the external surface of the cranial base: the prosthion, the staphylion, the hormion, the sphenobasion, and the basion (Laitman, 1978; Lieberman, 1999). Ontogenetic changes in exocranial flexion were then correlated with the positioning of the upper respiratory structures (Laitman *et al.*, 1978: 467-9; Lieberman and McCarthy, 1999: 491). Laitman observed that flexure of the basicranium correlated with the process of hyo-laryngeal descent, in which the tongue and larynx descend into their adult positioning in the neck by the second year of life (Laitman *et al.*, 1978: 467; Lieberman *et al.*, 2001: 119). Thus, Laitman concluded that exocranial flexion was directly correlated (at least structurally, and, possibly, functionally) to the position of the tongue and larynx as well as to the orientation of pharyngeal constrictor muscles – integral aspects of the formation of speech (Laitman *et al.*, 1987: 481).

While his earlier works describe the correlation between cranial base morphology and vocal tract structures, Laitman's later works, in 1982 and 1992, particularly Laitman *et al.* (1992), describe the airway's importance for speech formation (Lieberman *et al.*, 1992: 448). In humans, the descent of the posterior third of the tongue into the neck results in the formation of the upper anterior wall of the pharynx and the lowering of the larynx, which separates the epiglottis from the soft palate (Laitman *et al.*, 1982: 334). As a result of these changes, the supralaryngeal region of the pharynx is expanded (Laitman *et al.*, 1982: 334). As explained by Laitman, phonation, or the sounds that make up speech, are produced by the interplay of the larynx and the supralaryngeal vocal tract (SVT) (Lieberman *et al.*, 1992: 448). The larynx produces what is known as the *fundamental frequency* (F0), which is perceived as pitch by listeners (Lieberman *et al.*, 1992: 450). By contrast, the SVT filters phonemes into speech, thinning the acoustic energy more at some frequencies than others and producing *formant frequencies* (Lieberman *et al.*, 1992: 452). Thus, the SVT enables the production of vowels and consonants (Lieberman *et al.*, 1992: 454, 456). Raising and lowering the larynx, as occurs during speech, changes the length of the SVT, thus altering the formant frequencies and producing various pitches, as in the English vowels "i" and "u" (Lieberman *et al.*, 1992: 457, 462). In other words, the "baseline" pitch of an individual's voice is determined primarily by the length of the larynx and the resulting frequency is further modulated by the SVT.

Laitman's theories have sparked some controversy, encouraging critique and support from many sources. While Reidenberg *et al.* (1991) found evidence of a mechanical relationship between basicranial flexion and the position and angulation of the larynx and hyoid through experiments performed on rats, Philip and Daniel Lieberman, in collaboration with several other authors, have proven more skeptical (Lieberman *et al.*, 1992; Lieberman and McCarthy, 1999; Lieberman *et al.*, 2000; Lieberman *et al.*, 2001; Lieberman, 2007). Lieberman and McCarthy

(1999) and Lieberman *et al.* (2000) examined ontogenetic changes in CBA and determined that the larynx and hyoid continue to descend after the base of the cranium has become fully flexed (Lieberman and McCarthy, 1999: 117; Lieberman *et al.*, 2000: 155). In addition, Lieberman *et al.* (2001) argued that the rate of hyo-laryngeal descent is primarily constrained by the development of swallowing ability, or deglutition since the surrounding hard and soft tissue structures must remain proportionally stable throughout ontogeny to make deglutition possible (Lieberman *et al.*, 2001: 124). Therefore, Lieberman argues against Laitman's claim that the cranial base and other aspects of cranial morphology impact the rate and degree of hyo-laryngeal descent, nor can it be used to predict whether a fossil possessed modern adult human vocal tract morphology (Lieberman *et al.*, 2001: 126; Lieberman, 2007: 46; Laitman and Crelin, 1976; Laitman *et al.*, 1978).

However, although Lieberman attributes deglutition to the ontogeny of hyo-laryngeal descent, he does not rule out a correlation between aspects of cranial shape (particularly the shortening of the face and retraction of the palate under the cranium, both of which are associated with decreased CBA) and the rate of hyo-laryngeal descent (Lieberman *et al.*, 2001: 126). In fact, Lieberman considers structural and spatial constraints imposed by cranial base flexion to be the primary reason for the oropharynx's failure to expand during ontogeny (Lieberman *et al.*, 2001: 126).

Thus, as revealed by this brief review of the current literature surrounding the basicranium, cranial base flexure is influenced by a number of spatial relationships both within and beyond the cranium itself. None of the theories presented here are mutually exclusive, but rather supplement each other in an increasingly nuanced understanding of the complex spatial interactions that affect the morphology and ontogeny of the basicranium.

Growth Trends of the Basicranium

As revealed over several decades of study, the various cranial bones comprising and influencing the cranial base experience differential growth patterns, thus affecting the ontogeny of the cranial base. The three primary bones of the cranial base: the occipital, sphenoid, and ethmoid bones, ossify endochondrally in a pattern corresponding to the ossification of vertebrae (Kjaer, 1990; Kjaer *et al.*, 1993). Cartilaginous precursors of these bones develop around the 40th day of gestation, and ossification progresses caudo-rostrally from the basioccipital to the ethmoid (Kjaer, 1990). As a result, at birth, the main growth centers in the cranial base lie between the basisphenoid and the basioccipital (known as the spheno-occipital synchondrosis) and between the presphenoid and the frontal bones, which results in elongation between the frontal and sphenoid bones (Ford, 1958). At birth, between 30% and 60% of all craniofacial growth is complete (Myer, 1995). While the growth of the spheno-occipital synchondrosis continues into and beyond adolescence, growth ceases at the spheno-mesethmoid synchondrosis by age seven, and at the cribriform plate by age two (Ford, 1958). By age six, 80% of cranial base growth is complete (Myer, 1995).

Researchers have shown that various areas of the cranial base, depending on their origins and functions relative to the braincase and facial skeleton, follow either a neural or somatic pattern of growth. The neural pattern (or the growth pattern of the brain and associated structures) is characterized by rapid growth during early development, which begins to decrease around the second year of life, and eventually plateaus around seven to eight years (Simpson, 2014). By contrast, somatic growth patterns increase from birth to adulthood, with a growth spurt in adolescence (Simpson, 2014). Areas between the nasion and foramen caecum (Na-Fc) and between the sella and basion (S-Ba) follow the somatic growth pattern, while the sagittal length of the foramen magnum and the area between the foramen caecum and sella (Fc-S) follow a

neural growth pattern (Ford, 1958; Zuckerman, 1955). Upon closer examination, the anterior aspects of the cranial base more closely follow the growth of the facial skeleton, while the posterior regions of the cranial base follow the growth of the brain (or endocranial cavity) (Michejda, 1975).

Evidence of sexual dimorphism in basicranial growth has also been found. Boys were found to experience a growth spurt in overall cranial dimensions at puberty while girls did not, a factor which may affect the morphology of the basicranium (Lewis *et al.*, 1985). In a study comparing growth trends between boys and girls, Ursi *et al.* (1993) found that the timing of various growth events varied. While overall, the anterior cranial base reached mature form earlier than the posterior cranial base, followed by various elements of the facial skeleton, females tended to reach mature form earlier than males (Ursi *et al.*, 1993; Buschang *et al.*, 1983).

Also, important to note are trends of individual variation in craniofacial growth observed by several researchers making use of longitudinal data (Brodie, 1941; Björk, 1955; Zuckerman, 1955). While average values tend to show fairly constant increases or decreases in angulation, a closer examination reveals significant fluctuation around a mean angle value within one individual (Simpson, 2014).

Context for and Aims of the Present Study

The primary aim of the present study is to investigate and attempt to replicate a portion of the aforementioned investigation conducted by Lieberman and McCarthy in 1999, which is summarized here. In this study, Lieberman and McCarthy sought to fill a gap in the literature surrounding the specific processes of cranial base ontogeny in humans and non-human primates and the degree of variation in these processes both within and between these species. The authors explicitly identified three main questions: a) how do different measures of CBA differ

throughout ontogeny due to changing spatial relationships between cranial bones? b) what is the extent to which ontogenetic differences between humans and other species make otherwise comparable measures of CBA misleading? and c) to what extent does CBA affect pharyngeal dimensions?

To answer these questions, Lieberman and McCarthy compared CBA within and between longitudinal radiographs of humans and chimpanzees divided into age bins. Specifically, they compared five measures of CBA (four internal and one external) between humans and chimpanzees, examined the ontogeny of these five angle measures relative to pharyngeal growth, and tested whether pharyngeal dimensions could be estimated using these and other craniofacial measurements. Radiographs of the human sample were drawn from the Denver Growth Study. Their sample included 15 males and 13 females of European descent.

Results of their study showed that, in humans, there was a statistically significant ($P < 0.05$) difference in mean CBA between successive age intervals in all CBA before the age of 2, decreasing between 8.6° and 15.3° (depending on which CBA measure was used), yet there was no statistically significant change after 2 years of age. Similarly, CBA 5, the measure of external CBA, showed a cessation of flexion in humans by age 2. CBA 5 was not measured for *P. troglodytes*. Specifically, for all internal CBA (1-4), humans younger than 1 year and 9 months showed much higher flexion (more acute angulation) than all humans older than 2 years and 9 months, at a confidence interval of $P < 0.001$. This pattern of flexion is synchronous with brain growth in humans. In chimpanzees, all CBA continue to widen (extend) with age, showing a fairly linear increase (skeletal growth trajectory), statistically significant at $P < 0.05$. No significant difference was observed in CBA 1-4 between males and females across all age groups in either humans or chimpanzees. These results revealed that humans and chimpanzees are subject to different types and degrees of ontogenetic changes in the angle of the cranial base

(flexion vs. extension). Chimpanzees also experienced a higher degree of postcranial extension than H. sapiens (more than double), ranging between 15.5° and 27.1° (depending on which angle was used).

Correlations between internal CBA (CBA 1-4) and external CBA were significant, although fairly low (between 0.25 and 0.49). No statistically significant relationship was found between either internal cranial base angles (CBA 1-4) or the external cranial base angle (CBA 5) and the vertical and horizontal dimensions of the vocal tract. The authors, therefore, determined that the vocal tract experienced a skeletal growth trajectory, while all CBA corresponded more closely with a neural growth trajectory, plateauing by the second age bracket. However, the authors did find strong linear relationships between the hyoid, larynx, and the base of the mandible, as well as evidence of sexual dimorphism in hyoid depth (from the palatal plane), with a lower hyoid in males than females ($P < 0.05$).

Lieberman and McCarthy conclude that their results indicate that postnatal basicranial flexion is unique to humans, and most likely stimulated by the expansion of the brain. In contrast, the majority of cranial base extension in chimpanzees occurs after cessation of brain growth and is, therefore, more closely linked to facial growth than it is in humans. However, the authors acknowledge that some researchers (Cousin *et al.*, 1981; Zuckerman, 1955) have found the trajectory of cranial base angulation to be longer in humans, continuing to change up to between 4-8 years of age, significantly beyond the cessation of brain growth at age two. However, the authors attribute this difference to the use of cross-sectional samples rather than longitudinal.

Although the authors attribute these differences to sampling technique, the present study hypothesizes that this difference was too large to be due only to the use of a cross-sectional sample. Although cross-sectional studies can be less precise, an examination of the Cousin *et al.*

(1981) and Zuckerman (1955) studies revealed additional differences in sampling and methods not discussed by Lieberman and McCarthy. Although the 1981 study by Cousin *et al.* was examined, the authors' use of the vestibular method (measured in relation to the vestibular horizontal) is not conventional within the literature on human cranial anatomy and, as such, Cousin *et al.*'s measurements were ultimately not comparable to those employed by Lieberman and McCarthy. The Zuckerman (1955) study, however, was investigated more closely as a foil to Lieberman and McCarthy's conclusions surrounding basicranial ontogeny and is accordingly summarized below.

The goal of Zuckerman's study was simply to determine whether age-related basicranial changes occurred in humans. Zuckerman's investigation was conducted on a single sample of 190 skulls belonging to both sexes and multiple races. The samples were not separated and analyzed according to these categories, however. Although Zuckerman acknowledged that doing so may have introduced additional variation or obscured age-based differences, he argued that the sample size was too small to determine trends of any significance within such divisions. Despite this, within each of Zuckerman's age bins, the number of individuals was mostly comparable to Lieberman and McCarthy's sample size (13 girls, 15 boys), although Zuckerman's sample for the 9-14 age bin was quite small (4 individuals). Therefore, Zuckerman divided the skulls into the following age groups based on dental age: Under 1, 1-2, 3-5, 6-8, 9-14, 15-21, Adult, and Senile. Several points were marked using lead slugs, and the skulls were then X-rayed. The distances between various points (basion, opisthion, nasion, and prosphenion) were measured, and two diagnostic angle measures (foramino-basal and spheno-ethmoidal angles) were recorded. As an extra step, to correct for any error or parallax introduced by the radiographs, the same distances were measured on the skulls using calipers and all X-ray

measurements were converted to “actual” measurements (a step which was not possible for the sample used by Lieberman and McCarthy, or for the sample used in this study).

Results showed a markedly longer trend in cranial base flexion than that observed by Lieberman and McCarthy. By approximately age 8, the cranial base was determined to have completed only half of its total antero-posterior growth, as the basioccipital, basisphenoid, presphenoid, and ethmoid bones (which comprise various aspects of the cranial base) continue growing into adulthood. Although analysis of variance revealed significant differences within each age group, t-tests conducted at a significance of $P < 0.02$ showed the basicranium to be increasing significantly in length throughout development, with growth after puberty remaining significant. Comparable trends were observed in the nasion-pituitary point distance. However, no significant change was observed in the size of the foramen magnum following the eruption of permanent teeth, around 6-8 years of age. However, while significant growth trends were observed in the linear dimensions of the basicranium, changes in angulation were much less pronounced. Although the changes were small, analysis of variance indicated that differences in angulation were nevertheless significant across age groups. At a significance level of $P < 0.02$, flexion of the foramino-basal and spheno-ethmoidal angles increased significantly between the 1-2, 3-5, 6-8, and adult age groups.

Therefore, Zuckerman concludes that the posterior part of the basicranium ceases to grow earlier than the central and anterior parts, which continue to grow until and even beyond puberty. As a result of Zuckerman’s variable dataset (including individuals of multiple races) and the structure of his study, his results reveal only very general growth trends, yet do not capture individual or within-group growth patterns. By contrast, Lieberman and McCarthy do not consider the effects of race on their sample, as the Denver Growth Study dataset used in their analysis is composed only of children of European descent. Therefore, in comparing

Zuckerman's results to those obtained by Lieberman and McCarthy, factors worth considering include the type of sample (longitudinal or cross-sectional), the races and sexes included in the sample, and the measurements used to describe growth trends.

Therefore, the goals of this study are threefold: 1) to test Lieberman and McCarthy's (1999) conclusions concerning the stabilization of cranial base flexion at approximately age 2 using the Krogman Dataset, 2) to test whether observed trends in cranial base angulation vary according to race and sex, and 3) to determine whether differing sampling and measuring techniques capture different spatial relationships and therefore influence observed flexion patterns.

Chapter 2: Materials and Methods

Samples

The samples used in this study were taken from a collection of mixed cross-sectional and longitudinal radiographs collected by Dr. Wilton Krogman's KCRCGD Growth Study and housed at the Penn Museum of Archaeology and Anthropology.

Dr. Krogman (1903-1987), an American anthropologist and a pioneer in the fields of physical and forensic anthropology, was interested in human craniofacial and skeletal growth and development (J. Monge, personal communication, June 26, 2018). To that end, Krogman set out to develop standards of growth for normal, healthy children of elementary and high school age, founding the W.M. Krogman Center for Research in Child Growth and Development (KCRCGD) (J. Monge, personal communication, June 26, 2018). Beginning in 1948, Krogman collected cross-sectional and longitudinal data from a sample of several thousand children, including boys and girls of both African and European descent (Blacks and Whites) from the greater Philadelphia metropolitan area (J. Monge, personal communication, June 26, 2018).

The dataset includes extensive anthropometric measurements including height, weight, body mass index (BMI), as well as several thousand radiographs including hand/wrist, frontal (anterior-posterior), and lateral cephalograms (J. Monge, personal communication, June 26, 2018). The KCRCGD dataset is the largest longitudinal study ever conducted on child growth in the U.S., and the largest dataset in the world of people of African ancestry (J. Monge, personal communication, June 26, 2018). The X-ray images and physiological records collected during this study fill seventeen filing cabinets at the University of Pennsylvania (J. Monge, personal communication, June 26, 2018). The remainder of the dataset, which contains personal, social, and contextual information of all children studied, comprises a total of seventy-two filing

cabinets in the records of the National Collaborative Perinatal Project (NCPP) (J. Monge, personal communication, June 26, 2018).

Although at the time consent forms were not commonly used, participation was voluntary, and families were able to view their children's files and medical information at any time (J. Monge, personal communication, June 26, 2018). Due to the age of these materials, the dataset has been determined to have no current clinical significance (J. Monge, personal communication, June 26, 2018). In addition, as the data have no primary researcher or single permanent home, they are now considered "orphaned" (J. Monge, personal communication, June 26, 2018).

All identifying information was coded and de-identified prior to collection. Following a consultation with the Internal Review Board, this project was determined to be exempt from HSERA. Of the extensive information recorded for each individual, only case numbers, age, sex, and race were recorded in this study. Because the radiographs had already been collected as part of the initial KCRCGD study, no radiographs were taken by the author.

A total sample size of 39 individuals was examined, comprising 20 black individuals (10 male and 10 female) and 19 white individuals (10 male and 9 female) for a total of 148 radiographs. Initially, radiographs of 10 white females were collected, but the tenth was excluded, not only because her race had been incorrectly recorded and she was, in fact, black, but also because her age exceeded the bounds of this study.

Methods

In the interest of accuracy and to eliminate possible error introduced by dark or blurry radiographs, all hard-copy radiographs were scanned onto the computer. The scans were then uploaded into Adobe Photoshop, where brightness and contrast were adjusted to provide better

visibility. Landmark points and planes were identified and marked on the image of the radiograph in Photoshop, and the zoom function was used to ensure that the points were placed accurately and consistently. All angle measurements were made using Adobe Photoshop's ruler tool, which reported the marked angle to one decimal place.

All landmarks, planes, and angles used in this study were drawn from Lieberman and McCarthy (1999) and Zuckerman (1955). A total of seven angles were measured, five of which were drawn directly from Lieberman and McCarthy (CBA 1-5), and two of which were taken from Zuckerman (Z1-2). These angles were chosen in order to facilitate comparisons between the results of this study and the results obtained by Lieberman and McCarthy (1999) as well as to determine whether the angles measured by Lieberman and McCarthy and Zuckerman captured substantially different spatial relationships in angle ontogeny. Tables 2.1, 2.2, and 2.3 report the landmarks, planes, and angles identified and measured, including abbreviations and definitions for each as well as the source study (Lieberman and McCarthy 1999 or Zuckerman 1955) from which the point, plane, or angle was drawn.

Landmarks included: basion (Ba), sella (S), sphenoidale (Sp), foramen caecum (FC), hormion (H), sphenobasion (Sb), opisthion (Op), pituitary point (PP), prosphenion (Pr), and nasion (Na). However, over the course of this study, the quality of the Krogman radiographs necessitated some slight adjustment of the points Op and Pr in order to ensure that they were visible across all radiographs so that the points could be recorded consistently and accurately. The adjusted position of these landmarks is shown in Figure 2.

Planes were drawn between basion and sella (SP), sella and foramen caecum (FCP), sphenoidale to the planum sphenoidum point (PSP), basion to a point on the dorsal margin of the occipital clivus (CP), basion to the pituitary point (BP), and prosthion to nasion (PN).

The five angles identified by Lieberman and McCarthy (CBA 1-5) measured the angles between planes SP and FCP, S and PSP, CP and FCP, CP and PSP, and between points Ba-Sb-H, respectively. The two angles used by Zuckerman, the foramino-basal angle and the spheno-ethmoidal angle, designated Z1 and Z2 by the author, measured the angles between points Op-Ba-Pr, and planes BP-PN, respectively. Figure 1 (adapted from Lieberman and McCarthy's Figure 4, p. 497), shows all landmarks, planes, and angles used in this study. Figure 2 shows the corresponding landmarks and planes as identified by the author on a radiograph used in this study.

According to Lieberman and McCarthy, the four planes between which internal cranial base flexion (CBA 1-4) was measured were chosen because they capture the most important components of many other commonly used angles seen in other studies of the basicranium. Therefore, measuring the angles between the two prechordal planes (FCP and PSP) and the two postchordal planes (SP and CP) provides accurate composite measures of internal cranial base flexion that are comparable to measures obtained by other researchers. In this study, it was the decision of the author to incorporate two additional planes (BP and PN), taken from Zuckerman's study, in an attempt to capture any additional trends in angulation that Lieberman and McCarthy's angles had not. As evidenced by Figure 1, there is a considerable degree of overlap between the CP and BP planes. Although there was some divergence between these two planes across the sample of radiographs examined in this study, more often than not they lay within a few degrees of each other. In addition, occasional overlap or proximity was observed between the PN and PSP planes. Therefore, the angle measured between the BP and PN planes (Z2, the Spheno-ethmoidal angle) also captured trends of flexion between the prechordal and postchordal planes and was consequently expected to correlate fairly closely with one or more of the five CBA angles.

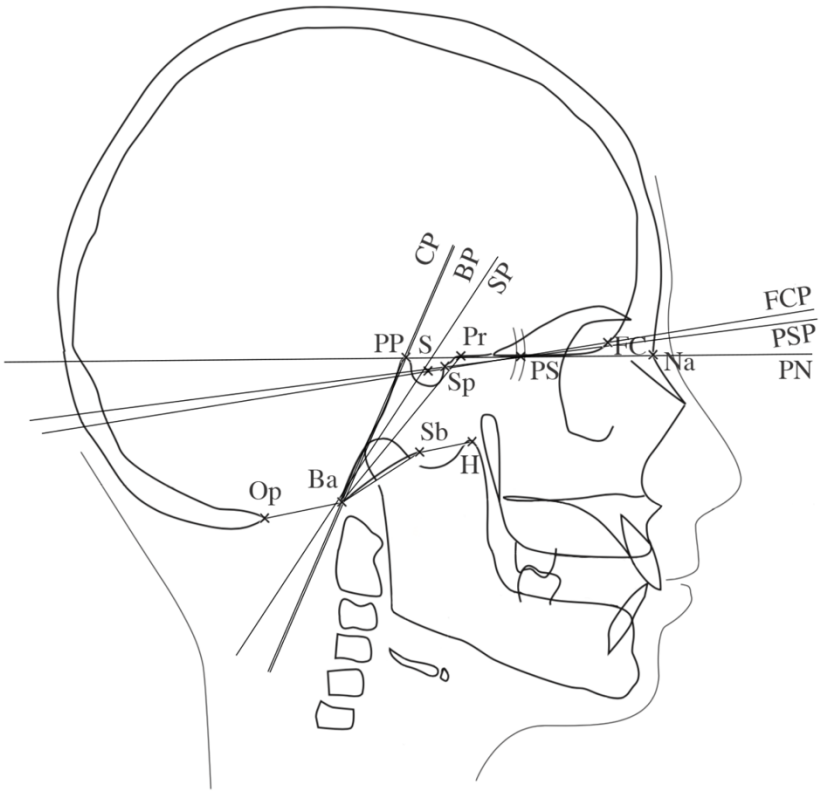

Figure 1. Simplified outline of lateral radiograph showing all landmarks and planes measured. See Tables 1.1, 1.2, and 1.3 for detailed descriptions (after Lieberman and McCarthy, 1999: 497).

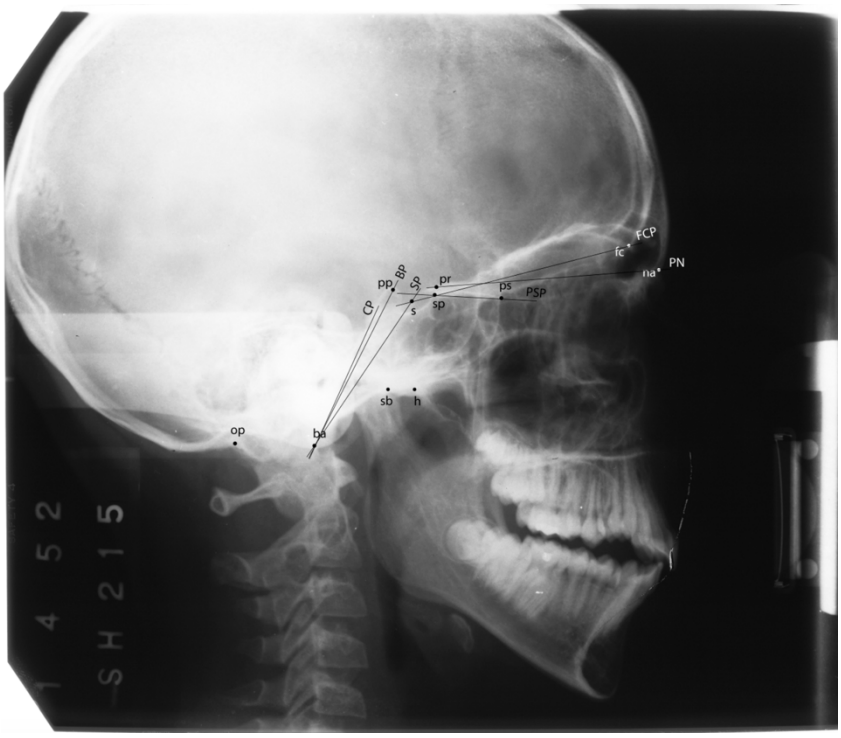

Figure 2. Landmarks and planes located on a radiograph used in this study. Landmarks are labeled in lowercase, and planes in capital letters.

Table 2.1: Landmarks used

Landmark	Abbreviation	Definition	Source
Opisthion	Op	Posterior point of the foramen magnum	Zuckerman, 1955
Basion	Ba	The midsagittal point on the anterior margin of the foramen magnum	Lieberman and McCarthy, 1999
Sphenobasion	Sb	The point in the middle of the spheno-occipital suture on the external portion of the clivus, at the junction of the basioccipital and sphenoid bones	Lieberman and McCarthy, 1999
Pituitary Point	PP	The anterior edge of the groove for the optic chiasma, just in front of the pituitary fossa	Zuckerman, 1955
Sella	S	The center of the sella turcica (determined independently of the contours of the clinoid process)	Lieberman and McCarthy, 1999
Sphenoidale	Sp	The most posterior and superior midline point on the tuberculum sellae	Lieberman and McCarthy, 1999
Planum Sphenoidum	PS	The superior-most point on the sloping surface of the pit in which the cribriform plate is set (as defined by Ross and Ravosa, 1993)	Lieberman and McCarthy, 1999
Hormion	H	Posterior-most midline point on the vomer	Lieberman and McCarthy, 1999
Prosphenion	Pr	The anterior limit of the presphenoid	Zuckerman, 1955
Foramen Caecum	FC	Pit on the cribriform plate between the crista galli and the endocranial wall of the frontal bone	Lieberman and McCarthy, 1999
Nasion	Na	The most anterior point of the frontonasal suture	Zuckerman, 1955

(after Lieberman and McCarthy 1999: 498 and Zuckerman 1955: 521)

Table 2.2: Planes used

Plane	Abbreviation	Definition	Source
Sella Plane	SP	Plane extending from basion to sella	Lieberman and McCarthy, 1999
Clival Plane	CP	Plane from basion to a point on the clivus before the dorsum sellae curves posteriorly	Lieberman and McCarthy, 1999
Focamen Caecum Plane	FCP	Plane from sella to foramen caecum	Lieberman and McCarthy, 1999
Planum Sphenoidum Plane	PSP	Plane from sphenoidale to the planum sphenoideum point	Lieberman and McCarthy, 1999
Basion Plane	BP	Plane from basion to the pituitary point	Zuckerman, 1955
Prosthion-Nasion Plane	PN	Plane from prosthion to nasion	Zuckerman, 1955

(after Lieberman and McCarthy 1999: 498 and Zuckerman 1955: 521)

Table 2.3: Angles measured

Angle	Measured between	Definition	Source
CBA 1	SP-FCP	Angle between the sella and foramen caecum planes	Lieberman and McCarthy, 1999
CBA 2	SP-PSP	Angle between the sella and pre-sphenoid planes	Lieberman and McCarthy, 1999
CBA 3	CP-FCP	Angle between the clival and foramen caecum planes	Lieberman and McCarthy, 1999
CBA 4	CP-PSP	Angle between the clival and pre-sphenoid planes	Lieberman and McCarthy, 1999
CBA 5	Ba-Sb-H	Angle between the external clival plane and the hormion plane, measured between basion, sphenobasion, and hormion	Lieberman and McCarthy, 1999
Z1	Op-Ba-Pr	Foramino-basal angle, measured between the basicranial axis and the plane of the foramen magnum	Zuckerman, 1955
Z2	BP-PN	Spheno-ethmoidal angle, measured between the basicranial axis and the presphenoid-nasion plane	Zuckerman, 1955

(after Lieberman and McCarthy 1999: 498 and Zuckerman 1955: 521)

Chapter 3: Results and Discussion

Results

Following Lieberman and McCarthy's example, in order to determine the average measurement error introduced as a result of inconsistent radiograph quality or human error, a single factor analysis of variants (ANOVA) was used to compare five sets of measurements, repeatedly taken from the same radiograph on five different days. The null hypothesis (H0) being tested was that all replicative measurements were the same. Results of the ANOVA showed that, for the most part, none of the angle measures recorded were statistically significantly different from each other. However, the fifth test appeared to differ significantly from test one and test two, but not from test three and test four – a relatively common outcome of repeated measures analyses. Measurement error averaged across all angles was ± 0.0028°.

Despite this fairly low measurement error, however, repeated angle measures taken at various time intervals revealed a significant amount of variation within each individual. Across every angle in every individual, fluctuation around a mean angle value was observed over time. These fluctuations most likely resulted either from measurement error or the cumulative effects of a small sample size and relatively few longitudinal data points. This tendency toward fluctuation in cranial base angulation has been observed by previous studies examining longitudinal data (Brodie, 1941; Björk, 1955; Zuckerman, 1955), although analyses conducted on all aggregated individuals tend not to be affected by this individual variation. In this study as well, as results will show, individual variation appeared not to be significant enough to reveal differences in cranial base angulation by age. However, no satisfactory explanation has yet been offered for this fluctuation.

Prior to conducting statistical analysis, univariate descriptive statistics (numerical and graphical) were generated for all seven cranial base angles grouped by age, sex, and race

categories using IBM SPSS statistical software in order to characterize each distribution. Once the assumption of normality was evaluated and accepted, means and standard deviations of each group (age, sex, and race) were compared, and the data were analyzed using single factor ANOVA and independent sample t-tests. A single factor ANOVA was used to examine trends in cranial base angle by age groups. Independent sample t-tests were used to examine trends in cranial base angle by sex and by race. Correlation between Lieberman and McCarthy's original five angles was then examined using least-squares (LSR) regression. The results of these analyses are presented below.

Statistical Description

Descriptive statistics were generated for all cranial base angles by age, sex, and race. From these statistics, the assumption of normality was accepted for all broader groups (age, sex, race).

Age

Because the ages of each individual sampled were recorded in decimal notation, the data were re-coded into age bins. While the majority of the samples fell between ages 9 and 16, many of the younger and older ages were represented by only one sample. With the exception of age bin 17, which was represented by 2 samples, and age bin 21, which was represented by 3 samples, all ages that were grouped into the 2-8 and 17-25 age bins were represented by only one sample each. As a result of these extremely small sample sizes, the more well-represented ages 9-16 were separated into age bins of width one year, while ages below 8 and above 16 were grouped into one age bin each. In all graphs and tables, age bin 0-8 is designated '8,' while age

bin 17-25 is designated ’17.’ Therefore, over a range of ages from 2 to 25, the data were split into nearly equal thirds.

Histograms generated for each angle across all age bins represented in multiple samples revealed that nearly all distributions approached the normal curve, although, age bins with fewer representative samples tended to be slightly skewed. A series of boxplots generated for each angle across all age bins revealed significant fluctuation around the mean. These boxplots are reproduced in Figure 3. Across all distributions, 95% Confidence Intervals for the mean showed significant overlap. The means, sample sizes, and standard deviations of all seven cranial base angles are reported for all age bins in Table 3.1.

Sex

Histograms generated for each angle by sex revealed distributions approaching the normal curve, although there did appear to be a slight tendency towards bimodality in the female distributions for CBA 2 and CBA 4, and a tendency towards bimodality in the male distribution in Z2. Nevertheless, measures of skewness were very low in all groups. Boxplots generated for male and female groups across all angles reveal a greater spread (greater range of data) in the male distributions for CBA 1-5, but a comparable spread between males and females in Z1, and a greater spread in the female distribution than in males in Z2. These boxplots are reproduced in Figure 4. 95% Confidence Intervals for the mean did not overlap for CBA 1, CBA 3, CBA 5, Z1 and Z2, although significant overlap was observed in CBA 2 and CBA 4. The means, sample sizes, and standard deviations for all cranial base angles in each sex category (male/female) are reported in Table 3.2.

Race

Histograms generated for each angle by race revealed distributions closely approaching the normal curve (although the distribution for whites for angle Z2 appeared to be slightly

bimodal). Measures of skewness were very low in all groups. 95% Confidence Intervals for the mean overlapped for the majority of the angles (CBA 1, CBA 3, CBA 5, Z1, and Z2), although overlap was not observed for CBA 2, CBA 4. Also worthy of note is that the number of radiographs is fairly different for each race category since a greater percentage of individuals sampled longitudinally were black. Therefore, n = 53 for the white sample while n = 94 for the black sample. Boxplots (Figure 5) reveal that the spread of the black sample was generally smaller than that of the white sample, likely due to sample size. The means, sample sizes, and standard deviations for all cranial base angles in each race category (black/white) are reported in Table 3.3.

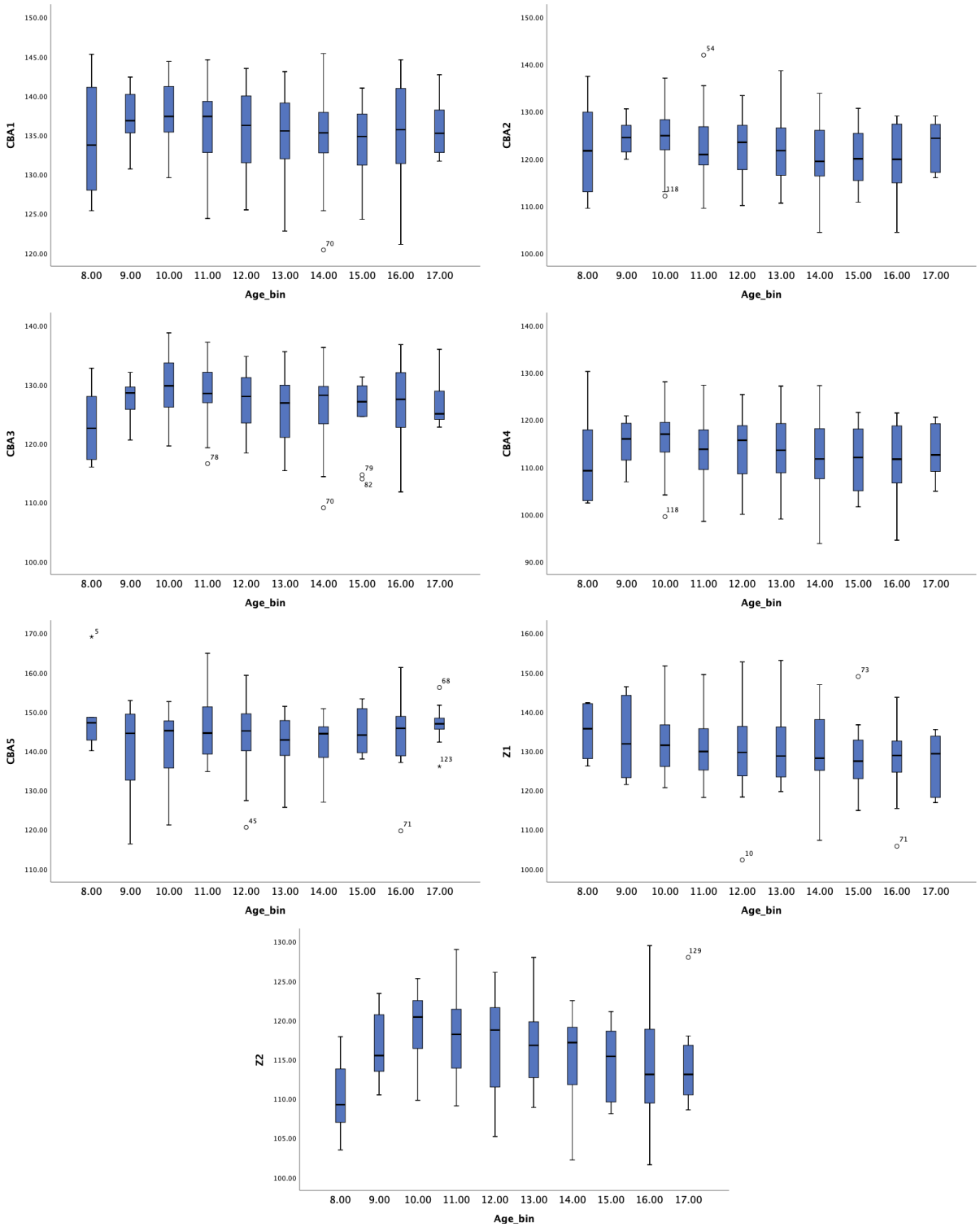

Figure 3. Boxplots showing the overall distribution of each angle by age bin. These data reveal significant fluctuation of angle measures around a semi-consistent median value. Open circles represent moderate outliers, while asterisks indicate extreme outliers. All outliers are labeled by case number

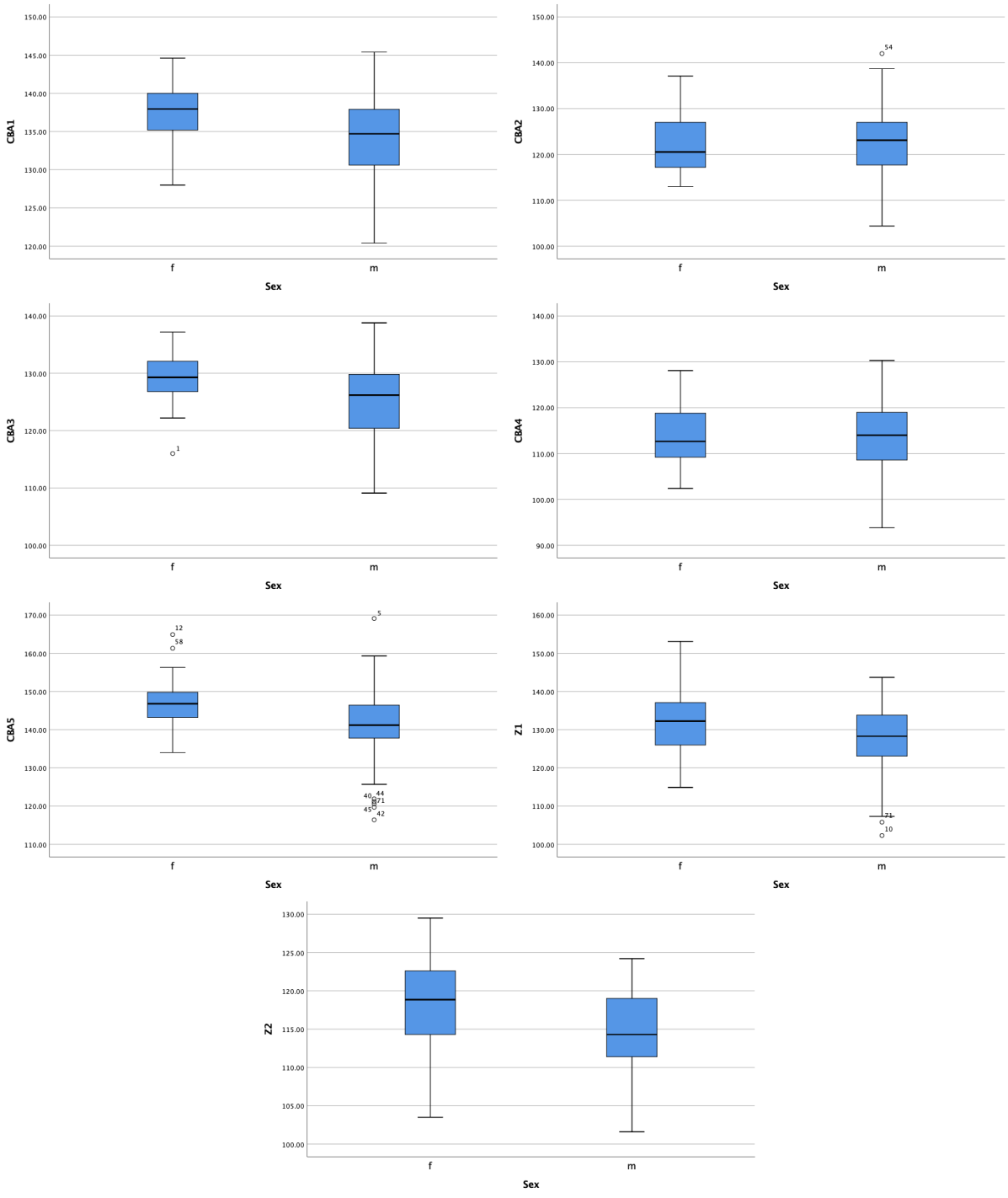

Figure 4. Boxplots showing the distribution of each angle by sex. Outliers are labeled by case number. Boxplots for all angles except Z1 and Z2 show the spread of cranial angles to be greater in males than in females.

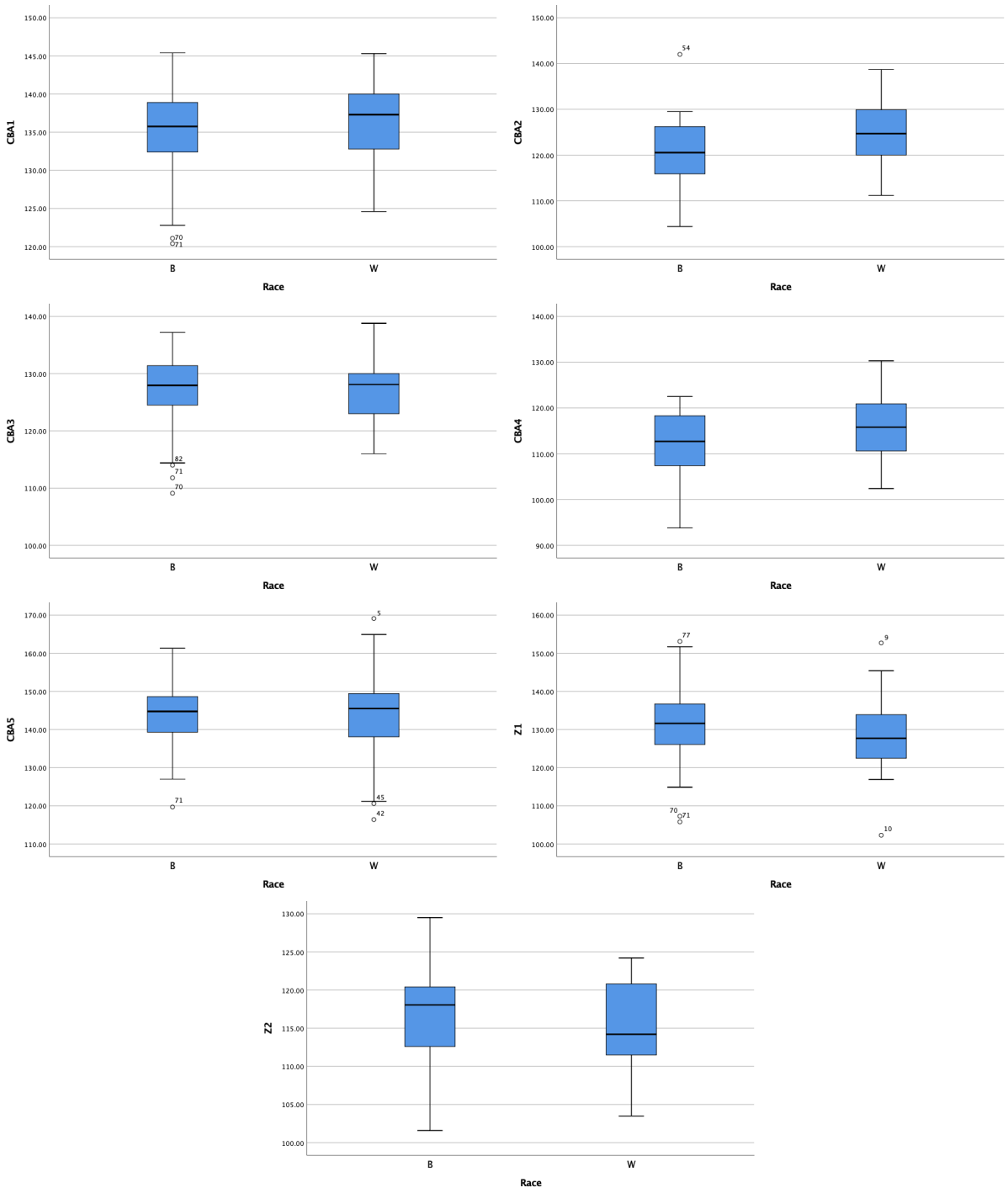

Figure 5. Boxplots showing the distribution of each angle by race. Outliers are labeled by case number. Descriptive statistics generated for CBA 2 and CBA 4 showed statistically distinct 95% Confidence Intervals for the mean. Spread is generally larger in the white sample, likely due to the effects of smaller sample size.

Table 3.1: Mean, sample size, and standard deviation of angles by age bins

Age_bin		CBA1	CBA2	CBA3	CBA4	CBA5	Z1	Z2
8.00	Mean	134.5500	122.2167	123.2167	112.0000	149.1667	135.0167	110.1167
	N	6	6	6	6	6	6	6
	Std. Deviation	7.98968	10.39739	6.87297	10.58149	10.28993	6.80218	5.15341
9.00	Mean	137.2250	124.5750	127.5875	115.1750	140.3000	133.3125	116.6625
	N	8	8	8	8	8	8	8
	Std. Deviation	3.69623	3.74690	3.66662	5.06945	12.34226	10.40885	4.50997
10.00	Mean	137.6048	124.5333	129.3524	116.2190	141.2667	131.8333	119.0190
	N	21	21	21	21	21	21	21
	Std. Deviation	4.13817	5.61109	5.13192	6.44466	9.32949	8.00683	4.88371
11.00	Mean	136.4609	123.0783	128.1826	114.0130	145.6174	130.5565	117.9696
	N	23	23	23	23	23	23	23
	Std. Deviation	5.03151	7.60460	5.20696	6.97745	8.18994	7.35928	5.26950
12.00	Mean	135.7682	122.3091	127.2591	113.8909	143.8818	130.8318	116.9682
	N	22	22	22	22	22	22	22
	Std. Deviation	5.10932	6.75933	4.79371	6.76242	9.25684	11.30619	5.43090
13.00	Mean	134.8450	121.8650	126.0150	113.1550	142.4450	130.2750	116.6950
	N	20	20	20	20	20	20	20
	Std. Deviation	5.61778	7.10724	5.67750	7.56533	6.43301	8.21942	5.53034
14.00	Mean	134.5250	120.0313	125.9812	111.5812	142.4688	130.2938	115.3937
	N	16	16	16	16	16	16	16
	Std. Deviation	5.84403	7.21080	6.73886	8.24283	5.98729	9.84699	5.23494
15.00	Mean	133.8200	120.1500	125.1700	111.6900	144.5800	129.0000	114.5500
	N	10	10	10	10	10	10	10
	Std. Deviation	5.36569	6.39327	6.11084	6.76419	5.64206	9.51607	4.65505
16.00	Mean	135.0909	120.5364	126.6364	112.0909	144.1727	127.4364	114.2455
	N	11	11	11	11	11	11	11
	Std. Deviation	7.30691	7.89408	7.68144	8.43866	10.70412	10.12050	7.74408
17.00	Mean	135.9600	122.7700	126.9500	113.3500	146.8000	127.5000	114.4800
	N	10	10	10	10	10	10	10
	Std. Deviation	3.66370	5.33917	4.45552	6.00190	5.30869	7.30571	5.59917
Total	Mean	135.7374	122.3102	127.0374	113.5626	143.7190	130.4980	116.3755
	N	147	147	147	147	147	147	147
	Std. Deviation	5.28695	6.83283	5.63973	7.15421	8.38499	8.93220	5.63549

Table 3.2: Mean, sample size, and standard deviation of angles by sex

Sex		CBA1	CBA2	CBA3	CBA4	CBA5	Z1	Z2
f	Mean	137.5455	122.2803	129.1455	113.9303	146.4212	132.7894	118.2545
	N	66	66	66	66	66	66	66
	Std. Deviation	3.67533	5.86689	4.04620	6.31484	5.89264	9.31428	5.86668
m	Mean	134.2642	122.3346	125.3198	113.2630	141.5173	128.6309	114.8444
	N	81	81	81	81	81	81	81
	Std. Deviation	5.92810	7.56550	6.17184	7.79781	9.44285	8.20095	4.97079
Total	Mean	135.7374	122.3102	127.0374	113.5626	143.7190	130.4980	116.3755
	N	147	147	147	147	147	147	147
	Std. Deviation	5.28695	6.83283	5.63973	7.15421	8.38499	8.93220	5.63549

Table 3.3: Mean, sample size, and standard deviation of angles by race

Race		CBA1	CBA2	CBA3	CBA4	CBA5	Z1	Z2
B	Mean	135.2957	120.6840	127.0298	112.1734	143.9330	131.6798	116.9191
	N	94	94	94	94	94	94	94
	Std. Deviation	5.58845	6.53007	6.06582	6.88872	6.62088	8.99244	5.71307
W	Mean	136.5208	125.1943	127.0509	116.0264	143.3396	128.4019	115.4113
	N	53	53	53	53	53	53	53
	Std. Deviation	4.65264	6.44690	4.84747	7.01137	10.89840	8.50790	5.41414
Total	Mean	135.7374	122.3102	127.0374	113.5626	143.7190	130.4980	116.3755
	N	147	147	147	147	147	147	147
	Std. Deviation	5.28695	6.83283	5.63973	7.15421	8.38499	8.93220	5.63549

Hypothesis Testing

The overall distributions of the seven cranial base angle measures were grouped by age bin, by sex, and by race, and statistical tests were performed on each group using IBM SPSS statistical software.

Age

A single factor ANOVA test was used to determine whether the fluctuations observed in cranial base angle across age groups were statistically significant at $\alpha = 0.05$. The null hypothesis (H0) being evaluated was that there is no significant difference in cranial base angle by age. A Test of Homogeneity of Variance was run, and the Levene statistic was not significant ($P > 0.05$)

for all cranial base angles. Therefore, the assumption of homogeneity of variance was determined to be tenable.

The single factor ANOVA test found no significant difference between the mean values of cranial base angles CBA 1-5 and Z1 ($P > .05$), although a significant difference by age was indicated in the Z2 angle measure ($P < .05$). The significance of the ANOVA test for Z2 was significantly below the critical value, at .026. The results of this test are replicated below, in Table 4.1. Interestingly, when the ANOVA was run without grouping the single-sample age groups together, no statistically significant difference was found in any of the angles, including Z2. However, the presence of sample sizes of $n = 1$ in so many of the age groups was not viable for statistical analysis, so the groups were compressed into age bins.

Therefore, as the assumption of homogeneity of variance was found tenable for all angle measures, and the ANOVA was not significant for angles CBA 1-5 and Z1, there is not sufficient evidence to reject the null hypothesis that no significant variation in these cranial base angles by age exists.

A Tukey's-b post-hoc test was conducted for the Z2 angle, as it was found to be significantly different by age bin by the ANOVA test. The Tukey's-b test revealed that, of the mean values of the Z2 angle for all age bins, age bin 8 (the aggregate of ages 2-8) was significantly different from age bins 10 and 11. However, age bins 10 and 11 were not significantly different from each other and age bins 8, 10, and 11 were also not themselves significantly different from age bins 9, 12, 13, 14, 15, 16, and 17. In other words, differences in means were significant for Z2 between age bins 8 and 10-11, indicating a possible change in angulation at that time. These results are represented in Table 4.2.

In addition, although the variation by age bin of all angles except Z2 was determined not to be statistically significant, plots of the mean angle at each age (produced by single factor

ANOVA) reveal interesting trends in the fluctuation of each angle. These plots are reproduced in Figure 6.

Table 4.1: ANOVA results for variation in cranial base angle by age bin for all individuals

		Sum of Squares	df	Mean Square	F	Sig.
CBA1	Between Groups	192.754	9	21.417	.755	.658
	Within Groups	3888.211	137	28.381		
	Total	4080.964	146			
CBA2	Between Groups	328.896	9	36.544	.772	.643
	Within Groups	6487.479	137	47.354		
	Total	6816.375	146			
CBA3	Between Groups	309.267	9	34.363	1.086	.377
	Within Groups	4334.497	137	31.639		
	Total	4643.764	146			
CBA4	Between Groups	316.156	9	35.128	.672	.733
	Within Groups	7156.529	137	52.237		
	Total	7472.684	146			
CBA5	Between Groups	643.419	9	71.491	1.018	.429
	Within Groups	9621.567	137	70.230		
	Total	10264.987	146			
Z1	Between Groups	442.949	9	49.217	.602	.794
	Within Groups	11205.540	137	81.792		
	Total	11648.489	146			
Z2	Between Groups	585.249	9	65.028	2.199	.026
	Within Groups	4051.523	137	29.573		
	Total	4636.772	146			

Table 4.2: Results of Tukey's-b post-hoc test for angle Z2

		Subset for alpha = 0.05	
Age_bin	N	1	2
8.00	6	110.1167	
16.00	11	114.2455	114.2455
17.00	10	114.4800	114.4800
15.00	10	114.5500	114.5500
14.00	16	115.3937	115.3937
9.00	8	116.6625	116.6625
13.00	20	116.6950	116.6950
12.00	22	116.9682	116.9682
11.00	23		117.9696
10.00	21		119.0190

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 12.025.

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

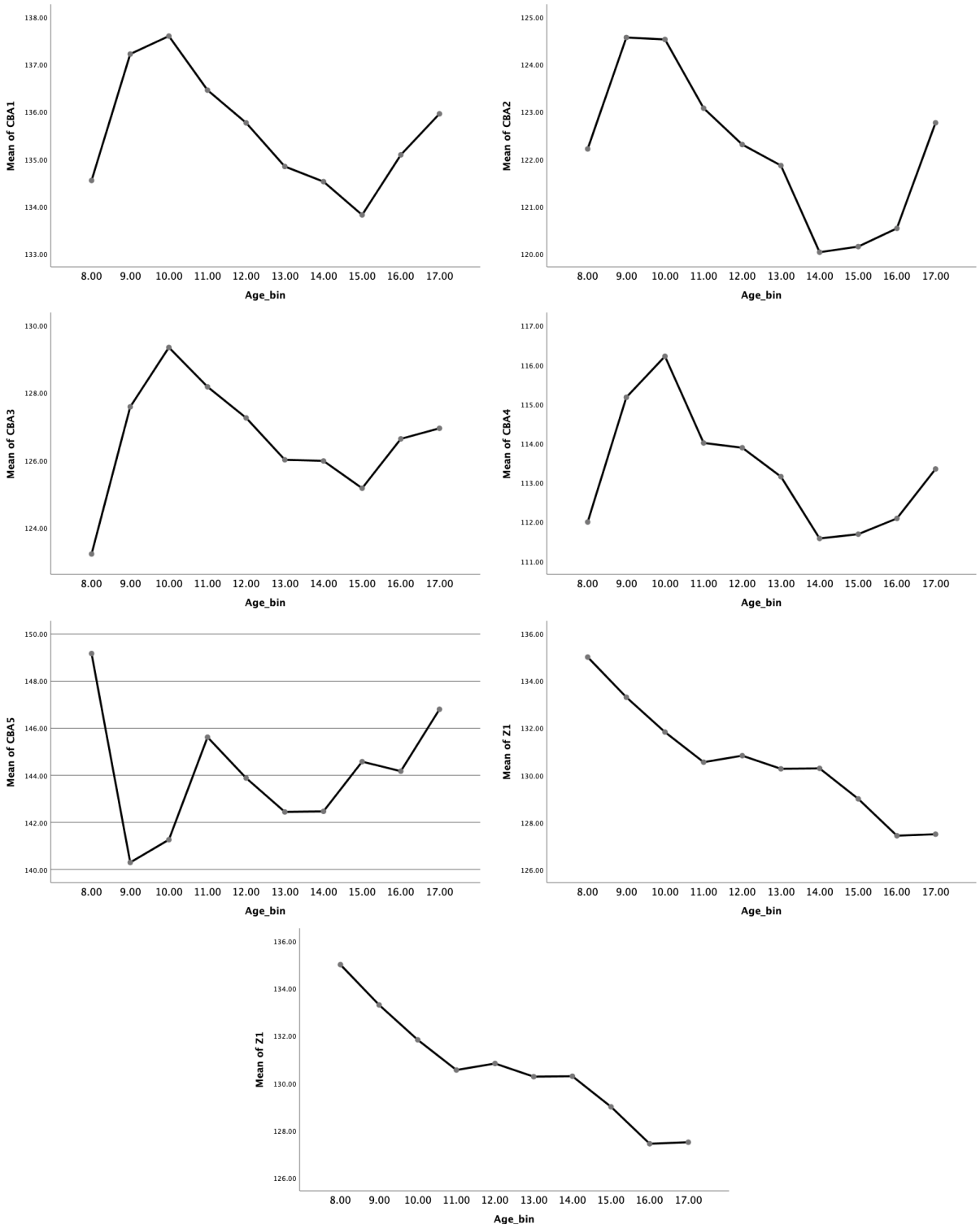

Figure 6. Mean plots for each cranial base angle by age bin. Although only Z2 is statistically significantly different across age bins, similar trends recur throughout.

Age trends examined by Sex and Race

Finally, in order to determine whether age trends were present within specific groups, ANOVA was used to explore trends in cranial base flexion across age bins by sex and by race. For all angles across all groups, the assumption of homogeneity of variance was accepted, as the Levene statistic was not significant for any group ($P > .05$). The single-factor ANOVA tests conducted found no significant difference in cranial base angle across age bins for any group, as significance values for all angles exceeded the critical value ($P > .05$). Therefore, the null hypothesis cannot be rejected, and no significant variation by age in cranial base angle is observed in males, in females, in blacks, or in whites. Although single-factor ANOVA indicated that the Z2 angle varied significantly by age, the source of the variation was unable to be identified when age bins were analyzed according to the four sex and race groups collected in this study. The ANOVA results for each sex are replicated in Tables 5.1 and 5.2, and ANOVA results for each race are replicated in Tables 5.3 and 5.4.

Table 5.1: ANOVA of angles by age bin for females

		Sum of Squares	df	Mean Square	F	Sig.
CBA1	Between Groups	176.116	9	19.568	1.561	.150
	Within Groups	701.907	56	12.534		
	Total	878.024	65			
CBA2	Between Groups	203.051	9	22.561	.621	.774
	Within Groups	2034.273	56	36.326		
	Total	2237.324	65			
CBA3	Between Groups	251.402	9	27.934	1.925	.067
	Within Groups	812.762	56	14.514		
	Total	1064.164	65			
CBA4	Between Groups	301.554	9	33.506	.819	.601
	Within Groups	2290.465	56	40.901		
	Total	2592.019	65			
CBA5	Between Groups	137.712	9	15.301	.404	.928
	Within Groups	2119.298	56	37.845		
	Total	2257.010	65			
Z1	Between Groups	942.580	9	104.731	1.249	.285
	Within Groups	4696.543	56	83.867		
	Total	5639.123	65			
Z2	Between Groups	514.316	9	57.146	1.858	.078
	Within Groups	1722.847	56	30.765		
	Total	2237.164	65			

Table 5.2: ANOVA of angles by age bin for males

		Sum of Squares	df	Mean Square	F	Sig.
CBA1	Between Groups	249.882	9	27.765	.770	.645
	Within Groups	2561.504	71	36.078		
	Total	2811.386	80			
CBA2	Between Groups	431.650	9	47.961	.821	.599
	Within Groups	4147.293	71	58.413		
	Total	4578.943	80			
CBA3	Between Groups	301.637	9	33.515	.867	.559
	Within Groups	2745.692	71	38.672		
	Total	3047.328	80			
CBA4	Between Groups	440.967	9	48.996	.786	.630
	Within Groups	4423.502	71	62.303		
	Total	4864.469	80			
CBA5	Between Groups	1114.019	9	123.780	1.460	.180
	Within Groups	6019.377	71	84.780		
	Total	7133.396	80			
Z1	Between Groups	293.112	9	32.568	.455	.900
	Within Groups	5087.341	71	71.653		
	Total	5380.453	80			
Z2	Between Groups	210.118	9	23.346	.938	.498
	Within Groups	1766.582	71	24.881		
	Total	1976.700	80			

Table 5.3: ANOVA of angles by age bin for blacks

		Sum of Squares	df	Mean Square	F	Sig.
CBA1	Between Groups	282.293	9	31.366	1.005	.443
	Within Groups	2622.165	84	31.216		
	Total	2904.458	93			
CBA2	Between Groups	340.828	9	37.870	.878	.549
	Within Groups	3624.858	84	43.153		
	Total	3965.686	93			
CBA3	Between Groups	346.748	9	38.528	1.052	.406
	Within Groups	3075.109	84	36.608		
	Total	3421.857	93			
CBA4	Between Groups	335.138	9	37.238	.767	.647
	Within Groups	4078.126	84	48.549		
	Total	4413.264	93			
CBA5	Between Groups	119.651	9	13.295	.282	.978
	Within Groups	3957.097	84	47.108		
	Total	4076.748	93			
Z1	Between Groups	721.099	9	80.122	.990	.455
	Within Groups	6799.252	84	80.943		
	Total	7520.352	93			
Z2	Between Groups	418.000	9	46.444	1.491	.165
	Within Groups	2617.446	84	31.160		
	Total	3035.446	93			

Table 5.4: ANOVA of angles by age bin for whites

		Sum of Squares	df	Mean Square	F	Sig.
CBA1	Between Groups	90.470	9	10.052	.418	.919
	Within Groups	1035.177	43	24.074		
	Total	1125.647	52			
CBA2	Between Groups	186.262	9	20.696	.451	.899
	Within Groups	1974.986	43	45.930		
	Total	2161.248	52			
CBA3	Between Groups	164.385	9	18.265	.743	.668
	Within Groups	1057.507	43	24.593		
	Total	1221.892	52			
CBA4	Between Groups	309.435	9	34.382	.658	.741
	Within Groups	2246.848	43	52.252		
	Total	2556.283	52			
CBA5	Between Groups	1149.782	9	127.754	1.093	.388
	Within Groups	5026.525	43	116.896		
	Total	6176.307	52			
Z1	Between Groups	447.740	9	49.749	.645	.752
	Within Groups	3316.250	43	77.122		
	Total	3763.990	52			
Z2	Between Groups	400.048	9	44.450	1.700	.119
	Within Groups	1124.225	43	26.145		
	Total	1524.273	52			

Sex

An independent samples t-test was used to describe the seven cranial base angles grouped by sex. T-tests were used to analyze cranial base angles by sex and race rather than single-factor ANOVA (as used by Lieberman and McCarthy), because ANOVA is appropriate for three or more groups, while sex and race are dichotomous variables, and therefore more suited to analysis via t-tests. The null hypothesis (H0) being tested was that there is no statistically significant difference in cranial base angle between sex groups. The number of samples (N), the mean, standard deviation, and the standard error of the mean for the male (m) and female (f) groups for each cranial base angle are reported in Table 6.1 below. Standard deviations for each angle by sex were quite high (with most values falling between approximately 5.8 and 9.4), indicating that the samples were smaller and the variation was higher than would be preferable in an ideal case. The results of the Levene Test for Homogeneity of Variance, the 95% Confidence Interval of the

difference in means between the male and female groups, and the results of the independent-samples t-test are reported in Table 6.2.

According to Levene's Test for Equality of Variances, equal variances cannot be assumed for CBA 1, CBA 3, and CBA 5, as the significance of the Levene statistic for those angles was lower than the critical value ($P < .05$). Therefore, the variances of the distributions of CBA 1, 3, and 5 are significantly different for males and females. Equal variances can be assumed for CBA 2, CBA 4, Z1, and Z2, as the significance of the Levene statistic for those angles was higher than the critical value ($P > .05$). This indicates that the distributions of these angles were not significantly different between males and females. Levene statistics are highlighted in Table 6.2.

Results of the t-tests showed that CBA 1, CBA 3, CBA 5, Z1, and Z2 had values of t that fell below the critical value ($P < .05$). Therefore, the null hypothesis (that there is no statistically significant difference between the mean angle of each sex group) can be rejected for these angles. T-values for angles CBA 2 and CBA 4, however, fell above the critical value ($P > .05$). The null hypothesis, therefore, cannot be rejected for these angles. These results are further substantiated by the 95% confidence interval of the difference between means of each sex group, which includes zero for those angles with a non-significant t-value ($P > .05$) and does not include zero for angles with a t-value of significance ($P < .05$). Interpreted t-values are highlighted in Table 6.2.

Table 6.1: T-test sex group statistics

	Sex	N	Mean	Std. Deviation	Std. Error Mean
CBA1	m	81	134.2642	5.92810	.65868
	f	66	137.5455	3.67533	.45240
CBA2	m	81	122.3346	7.56550	.84061
	f	66	122.2803	5.86689	.72216
CBA3	m	81	125.3198	6.17184	.68576
	f	66	129.1455	4.04620	.49805
CBA4	m	81	113.2630	7.79781	.86642
	f	66	113.9303	6.31484	.77730
CBA5	m	81	141.5173	9.44285	1.04921
	f	66	146.4212	5.89264	.72533
Z1	m	81	128.6309	8.20095	.91122
	f	66	132.7894	9.31428	1.14651
Z2	m	81	114.8444	4.97079	.55231
	f	66	118.2545	5.86668	.72214

Table 6.2: Levene Test, t-test, and 95% Confidence Interval for cranial base angles by sex

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
CBA1	Equal variances assumed	15.390	.000	-3.923	145	.000	-3.28126	.83645	-4.93446	-1.62805
	Equal variances not assumed			-4.106	136.025	.000	-3.28126	.79908	-4.86148	-1.70104
CBA2	Equal variances assumed	1.414	.236	.048	145	.962	.05426	1.13693	-2.19283	2.30136
	Equal variances not assumed			.049	144.673	.961	.05426	1.10822	-2.13613	2.24466
CBA3	Equal variances assumed	14.552	.000	-4.333	145	.000	-3.82570	.88300	-5.57091	-2.08049
	Equal variances not assumed			-4.514	139.042	.000	-3.82570	.84754	-5.50143	-2.14997
CBA4	Equal variances assumed	.830	.364	-.561	145	.576	-.66734	1.18912	-3.01760	1.68292
	Equal variances not assumed			-.573	144.997	.567	-.66734	1.16400	-2.96793	1.63325
CBA5	Equal variances assumed	8.881	.003	-3.675	145	.000	-4.90393	1.33445	-7.54142	-2.26644
	Equal variances not assumed			-3.845	136.396	.000	-4.90393	1.27552	-7.42627	-2.38158
Z1	Equal variances assumed	1.261	.263	-2.877	145	.005	-4.15853	1.44558	-7.01566	-1.30140
	Equal variances not assumed			-2.840	130.685	.005	-4.15853	1.46451	-7.05575	-1.26131
Z2	Equal variances assumed	.935	.335	-3.815	145	.000	-3.41010	.89392	-5.17690	-1.64330
	Equal variances not assumed			-3.751	127.765	.000	-3.41010	.90914	-5.20901	-1.61119

Variance in Sex examined by Race

Additional independent sample t-tests were conducted for each race in order to determine whether the variance observed between males and females was influenced in any way by race.

Black

According to Levene's Test for Equality of Variances, equal variances cannot be assumed for CBA 1, CBA 2, CBA 3, and CBA 4, as the significance of the Levene statistic was lower than the critical value ($P < .05$). This indicates that the distributions of these angles (coincidentally, Lieberman's four measures of internal cranial base flexion), show significantly different variance between black males and black females. Equal variances are assumed for CBA 5, Z1, and Z2 ($P > .05$), indicating that these distributions were significantly similar in variance between black males and black females. Levene statistics are highlighted in Table 7.2.

The results of the t-tests indicated that the means of all measures of cranial base angle except for CBA 2 were statistically significantly different between black males and black females. In other words, the significance of the t-value fell below the critical value ($P < .05$) for CBA 1, CBA 3, CBA 4, CBA 5, Z1, and Z2. Therefore, the null hypothesis can be rejected for nearly all angle measures, and a statistically significant variation by sex within the black sample can be claimed. Group statistics and t-test results are reported in Table 7.1 and 7.2. Interpreted t-values are highlighted in Table 7.2.

White

According to the Test for Equality of Variances, equal variances cannot be assumed for CBA 2, CBA 4, and CBA 5, as the significance of the Levene statistic was lower than the critical value ($P < .05$). This indicates that the distributions of these angles show significantly different variance between white males and white females. Equal variances are assumed for CBA 1, CBA 3, Z1, and Z2 ($P > .05$), indicating that these distributions were significantly similar in variance between white males and white females. Levene statistics are highlighted in Table 7.4.

The results of the t-tests indicated that only the mean of CBA 5 was statistically significantly different between white males and white females, as the significance of the t-value fell below the critical value ($P < .05$). For all other angles, no statistically significant difference was observed in the mean angle between white males and white females ($P > .05$). Therefore, only for CBA 5 can the null hypothesis be rejected, and a statistically significant variation by sex within the white sample claimed. Group statistics and t-test results are reported in Table 7.3 and 7.4. Interpreted t-values are highlighted in Table 7.4.

Table 7.1: t-test group statistics of CBA by sex for blacks

	Sex	N	Mean	Std. Deviation	Std. Error Mean
CBA1	m	46	132.8239	6.29960	.92883
	f	48	137.6646	3.47707	.50187
CBA2	m	46	119.5261	7.63985	1.12643
	f	48	121.7938	5.09144	.73489
CBA3	m	46	124.0957	6.82453	1.00622
	f	48	129.8417	3.42232	.49397
CBA4	m	46	110.4261	7.94337	1.17119
	f	48	113.8479	5.25693	.75877
CBA5	m	46	141.8674	7.22806	1.06572
	f	48	145.9125	5.34227	.77109
Z1	m	46	129.7239	7.88552	1.16266
	f	48	133.5542	9.65091	1.39299
Z2	m	46	114.6761	4.96714	.73237
	f	48	119.0688	5.59624	.80775

Table 7.2: Levene Test, t-test, and 95% Confidence Interval for cranial base angles by sex for blacks

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
CBA1	Equal variances assumed	12.154	.001	-4.638	92	.000	-4.84067	1.04371	-6.91356	-2.76778
	Equal variances not assumed			-4.585	69.444	.000	-4.84067	1.05574	-6.94658	-2.73476
CBA2	Equal variances assumed	6.279	.014	-1.700	92	.092	-2.26766	1.33387	-4.91684	.38151
	Equal variances not assumed			-1.686	77.940	.096	-2.26766	1.34496	-4.94530	.40997
CBA3	Equal variances assumed	22.498	.000	-5.192	92	.000	-5.74601	1.10660	-7.94382	-3.54821
	Equal variances not assumed			-5.126	65.653	.000	-5.74601	1.12093	-7.98425	-3.50778
CBA4	Equal variances assumed	12.294	.001	-2.473	92	.015	-3.42183	1.38381	-6.17020	-.67346
	Equal variances not assumed			-2.452	77.612	.016	-3.42183	1.39550	-6.20027	-.64339
CBA5	Equal variances assumed	2.811	.097	-3.095	92	.003	-4.04511	1.30715	-6.64122	-1.44900
	Equal variances not assumed			-3.075	82.738	.003	-4.04511	1.31542	-6.66156	-1.42866
Z1	Equal variances assumed	2.689	.104	-2.102	92	.038	-3.83025	1.82223	-7.44937	-.21114
	Equal variances not assumed			-2.111	89.784	.038	-3.83025	1.81444	-7.43507	-.22544
Z2	Equal variances assumed	.005	.946	-4.018	92	.000	-4.39266	1.09312	-6.56368	-2.22164
	Equal variances not assumed			-4.029	91.473	.000	-4.39266	1.09033	-6.55832	-2.22701

Table 7.3: t-test group statistics of CBA by sex for whites

	Sex	N	Mean	Std. Deviation	Std. Error Mean
CBA1	m	35	136.1571	4.86502	.82234
	f	18	137.2278	4.25162	1.00212
CBA2	m	35	126.0257	5.72077	.96699
	f	18	123.5778	7.58207	1.78711
CBA3	m	35	126.9286	4.82631	.81580
	f	18	127.2889	5.01983	1.18319
CBA4	m	35	116.9914	5.86201	.99086
	f	18	114.1500	8.71768	2.05478
CBA5	m	35	141.0571	11.84374	2.00196
	f	18	147.7778	7.15415	1.68625
Z1	m	35	127.1943	8.49758	1.43635
	f	18	130.7500	8.25550	1.94584
Z2	m	35	115.0657	5.03931	.85180
	f	18	116.0833	6.17654	1.45583

Table 7.4: Levene Test, t-test, and 95% Confidence Interval for cranial base angles by sex for whites

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
CBA1	Equal variances assumed	.254	.616	-.791	51	.433	-1.07063	1.35438	-3.78966	1.64839
	Equal variances not assumed			-.826	38.806	.414	-1.07063	1.29633	-3.69313	1.55186
CBA2	Equal variances assumed	5.895	.019	1.318	51	.193	2.44794	1.85677	-1.27968	6.17555
	Equal variances not assumed			1.205	27.244	.239	2.44794	2.03195	-1.71954	6.61541
CBA3	Equal variances assumed	.157	.694	-.254	51	.801	-.36032	1.41881	-3.20870	2.48807
	Equal variances not assumed			-.251	33.248	.804	-.36032	1.43717	-3.28343	2.56279
CBA4	Equal variances assumed	10.172	.002	1.410	51	.164	2.84143	2.01455	-1.20295	6.88580
	Equal variances not assumed			1.246	25.146	.224	2.84143	2.28121	-1.85543	7.53829
CBA5	Equal variances assumed	4.498	.039	-2.203	51	.032	-6.72063	3.05000	-12.84376	-.59751
	Equal variances not assumed			-2.568	49.513	.013	-6.72063	2.61749	-11.97931	-1.46196
Z1	Equal variances assumed	.442	.509	-1.456	51	.151	-3.55571	2.44151	-8.45725	1.34583
	Equal variances not assumed			-1.470	35.329	.150	-3.55571	2.41855	-8.46400	1.35258
Z2	Equal variances assumed	1.868	.178	-.644	51	.522	-1.01762	1.57926	-4.18811	2.15288
	Equal variances not assumed			-.603	28.936	.551	-1.01762	1.68671	-4.46766	2.43242

Race

An independent samples t-test was used to describe the cranial base angles grouped by race. The null hypothesis (H0) being tested was that there is no statistically significant difference in cranial base angle between racial groups. The number of samples (N), the mean, standard deviation, and the standard error of the mean for the black (B) and white (W) groups for each cranial base angle are reported in Table 8.1 below. Standard deviations were also fairly high by race, ranging between approximately 4.6 and 10.9, although most values fell closer to approximately 6.0. The results of the Levene Test for Homogeneity of Variance, the 95% Confidence Interval of the difference in means between the black and white groups, and the results of the independent-samples t-test are reported in Table 8.2.

According to Levene's Test for Equality of Variances, equal variances cannot be assumed for the distributions of CBA 5, as the significance of the Levene statistic was lower than the critical value ($P < .05$), indicating that the variance of the distributions is significantly

different between black and white racial categories. However, equal variances can be assumed for all other angles, as the significance of the Levene statistic lies above the critical value (P > .05), indicating no significant difference in the variance of the distributions between black and white racial categories. Levene statistics are highlighted in Table 8.2.

Results of the t-tests showed that CBA 2, CBA 4, and Z1 had values of t that fell below the critical value (P < .05). Therefore, the null hypothesis (that there is no statistically significant difference between the mean angle of each racial group) can be rejected for these angles. T-values of angles CBA 1, CBA 3, CBA 5, and Z2, however, fell above the critical value (P > .05). Therefore, the null hypothesis cannot be rejected for these angles. These results are further substantiated through the 95% confidence interval of the difference between means of each racial group, which includes zero for those angles with a non-significant t-value (P > .05) and did not include zero for angles with a t-value of significance (P < .05). Interpreted t-test values are highlighted in Table 8.2.

Table 8.1: T-test race group statistics

	Race	N	Mean	Std. Deviation	Std. Error Mean
CBA1	B	94	135.2957	5.58845	.57640
	W	53	136.5208	4.65264	.63909
CBA2	B	94	120.6840	6.53007	.67353
	W	53	125.1943	6.44690	.88555
CBA3	B	94	127.0298	6.06582	.62564
	W	53	127.0509	4.84747	.66585
CBA4	B	94	112.1734	6.88872	.71052
	W	53	116.0264	7.01137	.96309
CBA5	B	94	143.9330	6.62088	.68289
	W	53	143.3396	10.89840	1.49701
Z1	B	94	131.6798	8.99244	.92750
	W	53	128.4019	8.50790	1.16865
Z2	B	94	116.9191	5.71307	.58926
	W	53	115.4113	5.41414	.74369

Table 8.2: Levene Test, t-test, and 95% Confidence Interval for cranial base angles by race

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
CBA1	Equal variances assumed	.904	.343	-1.353	145	.178	-1.22501	.90559	-3.01487	.56485
	Equal variances not assumed			-1.423	124.824	.157	-1.22501	.86063	-2.92832	.47830
CBA2	Equal variances assumed	.003	.957	-4.039	145	.000	-4.51030	1.11659	-6.71720	-2.30340
	Equal variances not assumed			-4.054	109.141	.000	-4.51030	1.11258	-6.71536	-2.30523
CBA3	Equal variances assumed	1.165	.282	-.022	145	.983	-.02116	.97209	-1.94246	1.90014
	Equal variances not assumed			-.023	128.393	.982	-.02116	.91367	-1.82895	1.78663
CBA4	Equal variances assumed	.047	.829	-3.235	145	.002	-3.85301	1.19090	-6.20678	-1.49925
	Equal variances not assumed			-3.219	106.387	.002	-3.85301	1.19682	-6.22572	-1.48031
CBA5	Equal variances assumed	10.870	.001	.411	145	.682	.59336	1.44444	-2.26152	3.44823
	Equal variances not assumed			.361	74.099	.719	.59336	1.64541	-2.68513	3.87184
Z1	Equal variances assumed	.173	.678	2.163	145	.032	3.27790	1.51534	.28289	6.27291
	Equal variances not assumed			2.197	113.058	.030	3.27790	1.49198	.32204	6.23376
Z2	Equal variances assumed	.000	.988	1.565	145	.120	1.50783	.96326	-.39601	3.41167
	Equal variances not assumed			1.589	112.905	.115	1.50783	.94884	-.37201	3.38767

Angle Comparisons

Finally, the two major groups of cranial base angle (Z1-2 vs. CBA 1-5) were evaluated against each other using least-squares (LSR) regression, which compared the slope and intercept of a linear model of each angle. Table 9.1 summarizes the results of the regressions. For comparison, Table 9.2 reproduces the results of regression comparisons of CBA 1-5 (after Lieberman and McCarthy, 1999: 507).

Comparison of the correlation coefficients (r) between Z1 and CBA 1-5 and between Z2 and CBA 1-5 reveal strong linear correlations in Z2 vs. CBA 1 (r = .708) and Z2 vs. CBA 3 (r = .788). The correlation (r) of Z2 vs. CBA 5 is low, while Z2 vs. CBA 2 and CBA 4 are moderate. Correlation is comparatively much higher between Z2 and CBA 1-5 than between Z1 and CBA 1-5. Although the correlation of Z1 vs. CBA 1 is moderately high, correlation of Z1 with CBA 2-5 is low.

Table 9.1: Regression comparisons of cranial base angle groups (Z1 and Z2 vs. CBA 1-5)

Regression	LSR Intercept	LSR Slope	r
Z1 vs. CBA 1	38.352	0.679	0.402
Z1 vs. CBA 2	90.012	0.331	0.253
Z1 vs. CBA 3	62.184	0.538	0.34
Z1 vs. CBA 4	97.892	0.287	0.23
Z1 vs. CBA 5	73.479	0.397	0.372
Z2 vs. CBA 1	14.002	0.754	0.708
Z2 vs. CBA 2	57.844	0.479	0.58
Z2 vs. CBA 3	16.311	0.788	0.788
Z2 vs. CBA 4	58.976	0.505	0.642
Z2 vs. CBA 5	87.712	0.199	0.297

Table 9.2: Regression comparisons of cranial base angles CBA 1-5
(after Lieberman and McCarthy, 1999: 507)

Regression	*n*	LSR intercept (s.e.)	LSR slope (s.e.)	RMA slope (s.e.)	*r*
CBA 1 *vs.* CBA 3	342	− 34.87 (4.39)	1.20 (0.03)	1.33 (0.03)	0.90
CBA 2 *vs.* CBA 4	308	− 10.11 (2.56)	1.02 (0.02)	1.09 (0.02)	0.94
CBA 1 *vs.* CBA 2	303	34.45 (12.32)	0.64 (0.09)	1.68 (0.09)	0.38
CBA 1 *vs.* CBA 4	303	13.50 (13.26)	0.74 (0.10)	1.85 (0.10)	0.40
CBA 2 *vs.* CBA 3	305	96.00 (5.02)	0.26 (0.04)	0.78 (0.04)	0.33
CBA 3 *vs.* CBA 4	307	22.65 (8.94)	0.71 (0.07)	1.42 (0.07)	0.50
CBA 1 *vs.* CBA 5	273	67.79 (11.72)	0.63 (0.09)	1.54 (0.09)	0.41
CBA 2 *vs.* CBA 5	257	123.46 (7.26)	0.24 (0.06)	0.96 (0.06)	0.25
CBA 3 *vs.* CBA 5	275	82.20 (7.60)	0.56 (0.06)	1.14 (0.06)	0.49
CBA 4 *vs.* CBA 5	257	119.08 (6.03)	0.30 (0.05)	0.91 (0.05)	0.33

Discussion

Statistical testing showed no significant increase or decrease in cranial base angulation across age categories greater than two years old, although 5 of the cranial base angles were observed to differ significantly by sex, and 3 to vary significantly by race (with the Z1 angle varying by both sex and race). It was also determined that the Z1 angle captured a significantly different spatial relationship than CBA 1-5.

Age

As descriptive statistics showed, the distribution for the more central age ranges (9-16) approached normal due to larger sample sizes (approximately 10-20 individuals per age bin), while the lower and upper age bins tended to be more skewed due to lower sample size (6 and 10 individuals, respectively). While 95% Confidence Intervals revealed no significant difference in all cranial base angle measures across age groups, ANOVA analysis showed a significant increase in mean Z2 between age bins 8 (ages 2-8) and 10-11. Therefore, the angle Z2 appeared to increase (extend) significantly between age bins 8 and 11. Interestingly, this overall trend observed in Z2 is similar in timing to that described by Zuckerman, although his results indicated a decrease in, or flexion of the spheno-ethmoidal angle (Z2) with increasing age (Zuckerman 1955: 538), while these results show an increase in angulation (or extension).

Although the observed trends in Z2 may indicate that the angle captured an additional spatial relationship that resulted in the extension of the angle between the BP and PN planes around ages 8-11, a closer examination of age trends by sex and race casts doubt upon that assumption. When the data were broken down by sex and by race and angulation across age bins was examined, single-factor ANOVA tests showed no significant variation or trends. Therefore, the significant difference observed overall could not be attributed to any one sex or race category, potentially indicating that the significant result was due to a type I error (a false

positive). This is most likely due to the effects of small sample size (as halving an already small sample made trends more difficult to detect) as well as simply an increased degree of variation overall due to the aggregation of blacks and white, and males and females (as in Zuckerman's sample). Therefore, these results corroborate Lieberman and McCarthy's conclusions regarding sexual dimorphism in cranial base angulation, as Lieberman and McCarthy's examination of CBA 1-4 by sex found no statistically significant difference in angulation for all age groups (Lieberman and McCarthy 1999: 501).

The mean plots produced by the ANOVA test (Figure 6) were also included, as there is a great deal of similarity evident in trends of angulation. Although most of these fluctuations are not significant, it is worthy of note that CBA 1-4 showed nearly identical trends of angulation, peaking around age 10, while CBA 5 at first showed a marked decrease in angulation with the most flexion occurring at age 9, before increasing again to peak at age 11. On the other hand, the Z1 and Z2 angles showed nearly identical trends of angulation, characterized by a fairly linear decrease with a slight period of equilibrium between ages 11 and 14. Therefore, Lieberman's four measures of internal cranial base flexion, CBA 1-4, appear to correlate very closely with each other, as do Zuckerman's two measures. CBA 5, however, appears to capture a unique trend, possibly as it was intended (as stated by Lieberman and McCarthy) to be a measure of external base flexion which correlated with the soft tissue structures of the upper airway. In addition, the average angles for age bin 2-8 began low in CBA 1-4, yet began high in CBA 5 and Z1-2, indicating a potentially inverse relationship at earlier ages, which were also the site of conflicting conclusions by Lieberman and McCarthy (1999) and Zuckerman (1955) and Cousin *et al.* (1981) surrounding trends in angulation. However, it is important to bear in mind that the first and final data points produced on these mean plots are the average values of an aggregate of age bins that were condensed due to low sample size. In addition, as a single-factor ANOVA

determined, the difference in means between age bins for nearly all angles is not large enough to be significant, and as a result, no conclusions can be drawn about the significance of these trends in relation to each other. Further analysis with a larger sample size may either accentuate or eliminate these trends.

Sex

Although descriptive statistics (histograms) seemed to indicate some slight bimodal tendencies in CBA 2 and CBA 4 for the female sample and in Z2 for the male sample, these data approached the normal distribution closely enough to proceed with classical hypothesis testing as t-tests are relatively conservative at small sample sizes, which tend to have more uncertainty around them. The Levene statistic indicated that equal variances could not be assumed for CBA 1, CBA 3, and CBA 5, meaning that only in those three angles did the distributions of angulation in males and females show significantly different variance. These trends were not evident from the numerical or graphical descriptive statistics (see Figure 4).

Descriptive statistics also revealed differences in the spread of the distribution between males and females for some angles. As noted previously, in CBA 1-5, the distribution of angulation in the male samples had a greater spread than in females, although this trend is reversed in Z1-2. This appears to indicate that Z1 and Z2 capture different spatial relationships; however, this initial assumption is only slightly corroborated by regression analysis (discussed in more detail below).

According to hypothesis testing, the mean values of CBA 1, CBA 3, CBA 5, Z1, and Z2 were all determined to be significantly different between males and females across all age ranges. Results indicate that males and females show significantly different mean values for the majority (5/7) of the cranial base angles examined in this study. These results, therefore, corroborate previous works (such as Lewis & Roche, 1977 and Ursi *et al.*, 1993) that also

encountered significant differences in cranial base angle between males and females. Of those four angles, this study indicates a significant difference by sex in CBA 1 and CBA 3, indicating that the individuals sampled by Krogman appear to represent differing trends of angulation as measured between the planes SP-FCP and CP-FCP.

Interestingly, CBA 5, which was utilized by Lieberman and McCarthy as a measure of external cranial base flexion that they believed was most likely to correlate with pharyngeal dimensions, was shown by this analysis to be significantly different in males than in females. In humans, vocal pitch is a consistently sexually dimorphic trait. At puberty, males experience a thickening of the larynx and vocal cords, which does not occur in females. However, analysis of temporal trends in all cranial base angles by sex revealed no statistically significant changes in angulation in males around the time of puberty (between the ages of 12 and 16) compared to females. Therefore, these results do not support a correlation between cranial base angulation and the development of vocal pitch dimorphism in humans.

Based on the analyses of sexual dimorphism in cranial base angle by race conducted above, it appears as though the majority of variation between males and females was introduced by the black sample. However, it is important to bear in mind that the black sample was nearly twice the size of the white sample, and, as a result, exerted a larger influence on cumulative analyses.

Race

Descriptive statistics produced for each angle measure by racial category showed that all distributions closely approached normal, apart from Z2, in which the white sample appeared to be very slightly bimodal. Of the confidence intervals for the mean, only CBA 2 and CBA 4 showed no overlap, indicating that the mean angle value was significantly different for only those two angles. According to the Levene statistic, the distribution of CBA 5 was significantly

different between black and white categories, while all other angles showed similar distributions between both categories.

Hypothesis testing revealed that CBA 2, CBA 4, and Z1 were significantly different between blacks and whites across all age groups. These results indicate that fewer than half the angles measured (3/7) showed significant variation by race. As a point of note, although numerical descriptive statistics generally proved to be an accurate predictor of emergent trends indicated by hypothesis testing, the significant difference found in the distribution of Z1 was not previously represented by the confidence interval generated for the mean. These results, therefore, suggest that the angles CBA 2 (SP-PSP), CBA 4 (CP-PSP), and Z1 (Op-Ba-Pr) capture trends in spatial relationships of the basicranium that vary significantly by race.

Interestingly, the Z1 angle was the only angle shown to be statistically significantly distinct between both sex and racial categories. In order to determine whether trends seen in this angle measure differ significantly from those patterns captured by CBA 1-5, a least-squares (LSR) regression was used.

Angle Comparisons

LSR regression was used to compare the slopes, intercepts, and correlation coefficients of Z1 and Z2 vs. CBA 1-5. Since Z1 and Z2 were included in this study primarily to determine whether Zuckerman's two angle measures captured substantially different trends of cranial base angulation than did Lieberman and McCarthy's five angles (CBA 1-5), comparisons using regression were able to test the correlation between them (Table 5). As evidenced by Figure 1, there is a great deal of overlap between the CP plane (from Lieberman and McCarthy) and the BP plane (from Zuckerman). Also, there is occasional overlap between Lieberman and McCarthy's PSP plane and Zuckerman's PN plane. Therefore, the angle measured between the BP and PN planes (Z2) was expected to correlate fairly strongly with at least one of Lieberman and McCarthy's angles. This expectation was supported by the results of the regression.

Results of the regression showed a strong correlation between Z2 and CBA 1 and between Z2 and CBA 3, as well as moderate correlations between Z2 and CBA 2, Z2 and CBA 4, and Z1 and CBA 1. Therefore, trends of significant variation in angulation by sex and race should be reexamined with these correlations in mind. In terms of variation by sex, for which angles CBA 1, CBA 3, CBA 5, Z1 and Z2 were found to be significantly different, angles Z1 and Z2 do not appear to reveal any new trends. Z2 correlates strongly with both CBA 1 and CBA 3, and Z1 correlates moderately with CBA 1, CBA 3, and CBA 5. It is, therefore, unlikely that these angles reveal any additional spatial variation in this case.

With respect to difference by race, however, it appears that the Z1 angle does capture an additional source of variation. Significant differences were found by race for angles CBA 2, CBA 4, and Z1. Z1 correlates only weakly with both CBA 2 and CBA 4, and it is, therefore, less likely that those angles influence trends in Z1. In addition, Z1 correlates most strongly with CBA 1, which was not found to be significantly different by race. Therefore, it appears that Z1 was able to summarize a meaningfully different spatial relationship than Lieberman and McCarthy's angle measures that varies in terms of race.

Interestingly, for those angles measured between two planes, trends seemed to be driven primarily by prechordal planes. For example, CBA 1 and CBA 3 were both determined to be dimorphic by sex and were measured between the SP-FCP and CP-FCP planes, respectively. Similarly, CBA 2 and CBA 4, measured respectively between the SP-PSP and CP-PSP planes, were determined to be dimorphic by race. Therefore, angles sharing the same prechordal plane (either FCP or PSP) tended to follow similar trends in dimorphism of the mean. Although the SP and CP planes lie near each other (Figure 1), according to regression analysis done by Lieberman and McCarthy, two angles that share the SP plane (CBA 1 and CBA 2) are only weakly correlated ($r = .38$), while two angles that share the CP plane (CBA 3 and CBA 4) are moderately

correlated (r = .50). A comparison of CBA 1 to CBA 3, however, reveals an extremely strong linear correlation (r = .90). CBA 2 and CBA 4 are even more strongly correlated (r = .94), indicating that the influence of the FCP and PSP planes on the resulting angle measure is comparatively stronger than that of the SP or CP planes. Therefore, it seems likely that dimorphic trends in the prechordal area of the cranium, such as facial kyphosis, are responsible for the statistically different means observed between sexes and races in these angles.

Chapter 4: Conclusion

Summary of Results

With regards to the initial question asked by this study – whether the use of samples including individuals of multiple races influenced Zuckerman's and Lieberman and McCarthy's differing conclusions surrounding the ontogeny of basicranial flexion – these results show that, in a sample including individuals from multiple races, significant basicranial flexion was observed only in angle Z2 (Zuckerman's spheno-ethmoidal angle). However, an analysis of flexion across age bins by sex and by race showed no significant changes for any sex-race grouping. Therefore, because the temporal variation in angulation seen in Z2 overall was not able to be detected within individual groups, it was most probably the result of variation introduced by measurement error or by the collective presence of multiple races and sexes. However, it is important to note that sample sizes for each of the examined sub-categories were also quite small (20b, 19w, 20m, 19f), and may have therefore failed to reveal trends that would have been evident with a larger sample. In addition, temporal fluctuation around a mean angle value was observed within all individuals for all angles – a phenomenon which occurred despite fairly accurate point placement and angle measurement. However, this fluctuation appeared to be consistent regardless of sex or race and was not indicated by hypothesis testing for angles by age. This occurrence has been noted by other researchers but has yet to be explained. One possible explanation may be that changes in facial morphology and body size coupled with the influence of environmental factors and daily life may result in small changes to the basicranium which, once aggregated into a larger sample, are not significant.

These results only partially corroborate Zuckerman's conclusion that the central and anterior parts of the basicranium continue to grow until puberty, as a significant difference was observed in the Z2 angle (borrowed from Zuckerman) beyond age 2, although these results

demonstrate extension rather than flexion. Although the observance of changes in basicranial flexion in the adolescent age ranges is common to both Zuckerman's results and the results of this study, the observance of extension rather than flexion may be reflective of additional characteristics that are different between Zuckerman's sample and the sample examined in this study. Also, the pattern of extension observed in this study may be related to small sample sizes. In that case, it is possible that an analysis conducted with a larger sample would more closely reflect Zuckerman's findings.

Ultimately, despite a smaller than desired sample size, the results of this study indicate that Zuckerman's use of a mixed-race sample was likely not the driving factor behind his observed ontogenetic trends in cranial base angulation since no individual group examined by the present study showed significantly different trends in angulation over time. Consequently, this study primarily corroborates Lieberman and McCarthy's conclusions concerning the cessation of flexion after age 2 and the absence of sexual dimorphism by age group. However, the inclusion of multiple races certainly introduced additional variation, which, in this study, may have manifested as significant variation in the Z2 angle by age overall. Similarly, Zuckerman's sample, which consisted of many races and sexes, also may have been affected by this cumulative variation.

Significant variation in cranial base angulation was also observed according to race and sex. Although no definitive trends in angulation were observed, since fluctuations by age within sex and race groups were not significant, the average means between both groups differed by a significant amount, indicating different spatial relationships between the prechordal and postchordal planes between the sexes and the races. In addition, race appeared to be a significant contributor to observed patterns of sexual dimorphism in mean cranial base angle. Analyses of sexual dimorphism for each racial category showed that the black sample had a much higher

degree of sexual dimorphism than the white sample. However, it must be acknowledged that the black sample (n = 94) was nearly twice the size of the white sample (n = 53), which may have influenced trends detected by statistical analysis. Nevertheless, this study was able to identify race as another source of variation which Lieberman and McCarthy did not consider (due to their use of an entirely European-heritage dataset).

In terms of the specific variation between sexes and races, it appears as though the angles which vary by sex (CBA 1, CBA 3, CBA 5, Z1, and Z2) are a nearly complete inverse of the angles which vary by race (CBA 2, CBA 4, and Z1). This appears to indicate that the variation that is present between the sexes is distinct from the variation that is present between races. Although Z1 was observed to differ significantly by sex and by race, regression analysis of the various angles against each other indicates that Z1 correlates most strongly with CBA 1, CBA 3, and CBA 5, yet only weakly with CBA 2 and CBA 4. Therefore, Z1 should have behaved fairly similarly to CBA 1, 3, and 5. The fact that Z1 was observed to vary by race as well was an interesting result, and trends of variation may become more evident with larger sample sizes. Although this may indicate a slight overlap in the spatial placement of variation by sex and by race, it also may be reflective of measurement error, or high variation due to small sample size.

CBA 5 in particular, which was originally intended by Lieberman and McCarthy to illustrate external cranial base flexion in terms of pharyngeal dimensions and position, was observed to vary significantly by sex. This difference was initially a point of interest, as Laitman (1976, 1978, 1982, 1992) had proposed that the basicranium might exert a structural influence on the upper airway, particularly on the pharynx, and may, therefore, be related to the production of speech. In addition, vocal pitch is distinctly sexually dimorphic in humans, lowering in males at the onset of puberty, around the ages of 12-16. However, when all cranial base angles were analyzed across age bins by sex, no significant trends of flexion or extension were observed in

males at puberty. Consequently, this study cannot conclude that vocal pitch changes are related to the morphology of the basicranium, or to the structural influence that it may exert on the airway. Therefore, it remains most likely that vocal pitch dimorphism in humans is the result of hormonal changes that occur at puberty (Dabbs and Mallinger, 1998; Puts *et al.*, 2006; Dixson, 2009).

The results of these analyses by age, sex, and race, as well as additional segregation and analysis conducted of age trends by sex, age trends by race, and sexual dimorphism by race, reveal that the angles used by both researchers did, in fact, quantify slightly different spatial relationships between cranial bones, although all measures were correlated to some degree. Overall, dimorphism of the cranial base angle was observed by sex and by race, although no notable temporal trends could be detected by either category. Also, the sample drawn from the Krogman dataset that was used in this study appeared to reveal differing trends in cranial base angle to those observed in both the Lieberman and McCarthy and Zuckerman studies. Although it is possible that these differences are due to the small sample sizes relied on by these analyses, both Lieberman and McCarthy and Zuckerman also made use of comparable sample sizes. Since smaller than desired sample sizes in this and other studies may be the source of some of the previously discussed variation, perhaps larger samples would be more conducive to identifying the source of the variation identified here. Regardless, as indicated by the results presented above, basicranial flexion and its variation by age, sex, and race is a more complex phenomenon than either Lieberman and McCarthy or Zuckerman described. Therefore, it is perhaps not so easily described by a single model that is common across all groups, or even across all samples. As a result of these findings, this study further contributes to the literature surrounding not only the complex structure of the basicranium but also the ongoing inquiry into the evolution of the human voice.

Further Study

Although the questions asked by this study would benefit from a re-examination using a larger sample size, additional avenues of inquiry exist. For instance, although the samples were divided into racial categories, no allowance was made for the nuances within those categories. As noted by Franz Boas, individuals of multiple races that are born and raised within the same cultural context display similarities in cranial dimensions (Boas, 1912). Therefore, in light of Boas's conclusions that cranial dimensions, and perhaps facial morphology as well, are highly dependent on environmental factors, a simple racial dichotomy may not be the most revealing way to explore differences in basicranial morphology. This is especially true, as the majority of the samples examined in this study were drawn from West and North Philadelphia, and therefore represent a relatively narrow range of geographic variation. Also, upon closer inspection, it appears that the majority of the individuals that made up the white sample examined by this study are of Russian or Ukrainian heritage. Therefore, a re-examination of previous conclusions in this light may be revealing, particularly as it concerns the comparatively lesser degree of sexual dimorphism in basicranial flexion observed in the white sample compared to the black sample.

In conclusion, a useful follow-up study to the research presented here would examine multiple groups within each broader racial group to determine whether a) individuals of various races sampled from the same cultural context reveal convergence in patterns of basicranial angulation, and b) subsets within larger racial categories are characterized by varying degrees of basicranial flexion. This study, which should ideally be conducted on a larger sample size than presented here, may be able to uncover more nuanced patterns of basicranial flexion, if any exist, within each racial group. The Krogman dataset would be well suited to this proposed

continuation of the study, as the KCRCGD Growth Study collected extensively detailed information surrounding the social and economic conditions, nutritional condition, and disease profiles of each individual sampled. This comprehensive picture of the social context of each individual provides a unique picture into the developmental circumstances and potential environmental factors influencing child growth.

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[i] Herodotus noted the occurrence of skulls without sutures and characterized Persian skulls as "more slender" than those of the Egyptians (Meijer, 1999: 101, from Paul Topinard, *Elements d'anthropologie generale* (Paris: Delahaye and Lecrossnier, 1885), p. 67)

[ii] As a result of Washburn's transformative ideas, the modern form of physical anthropology (now often referred to as biological anthropology) now defines itself as "a biological science that deals with the adaptations, variability, and evolution of human beings and their living and fossil relatives. Because it studies human biology in the context of human culture and behavior, physical anthropology is also a social science (Fuentes, 2010: 2)."

[iii] X-Rays themselves were discovered in 1895 by German professor Wilhelm Conrad Roentgen (1845-1923), although the technology was not widely applied to medicine until 1931 (Finlay, 1980: 320-321).